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Start with steel

A practical plan to support carbon workers and cut emissions

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Overview

Australia has an historic opportunity to create a new, export-focused manufacturing sector based on globally competitive renewable energy. The opportunity is more than building wind and solar farms – we can use wind and solar to make energy-intensive 'green' commodities.

If we get it right, we will resolve a climate conundrum that has stretched our political fabric for more than a decade.

Australians are very exposed to the effects of climate change – through our health, our agriculture, and our tourism – but we are also a large exporter of fossil fuels. Our climate politics reflect this. In the 2019 federal election, regions with many 'carbon workers' – workers in industries such as coal mining, fossil fuel power generation, and aluminium smelting – swung strongly towards the Coalition with its less ambitious climate targets. Labor's assurances of a 'just transition' to a low-emissions future failed to resonate. But new clean energy industries can create tens of thousands of jobs – comparable to those in existing carbon-intensive industries. And these jobs could be in the same regions that host carbon-intensive industry today.

In this report, we assess the potential of three sectors that could help make Australia a green energy 'superpower': aviation fuel, ammonia, and steel. Our analysis concludes that green steel represents the best opportunity for exports and job creation in key regions.

Green steel uses hydrogen, produced from renewable energy, to replace metallurgical coal to reduce iron ore to iron metal. Australia's renewable resources make it a lower-cost place to make hydrogen, and therefore green steel, than countries such as Japan, Korea and Indonesia. But to do this at a global scale, Australia will also need a large industrial workforce – such as those found in central Queensland and the Hunter Valley in NSW. It is cheaper to make green steel in those places, where labour is available and affordable, than in the Pilbara in Western Australia – despite the cost of shipping iron ore to the east coast.

Investment at a global scale must come from the private sector. But Australian governments should act now to ensure we can capture this opportunity. The key is building local skills and capability in low-emissions steel-making in the next decade. This is best achieved through government funding to support a steel 'flagship' project. This could involve gas instead of hydrogen in the interim, providing a lower-cost and commercially proven path to green steel. Western Australia, with its low-cost gas, could play an important role. And moving towards lower-emissions steel could help sustain existing steel-making jobs in Port Kembla in NSW or Whyalla in South Australia.

Low-cost hydrogen storage will be an important part of the process. Governments should fund and publish pre-commercial studies of the geological potential in Australia for hydrogen storage. And federal, state, and local governments should all play a role in coordinating land-use planning and regional development, and in supporting workforce retraining.

Australia can also support a new, sustainable biofuels industry that uses non-food biomass sources. The federal government should investigate the costs and benefits of a policy requiring a share of domestic aviation fuel to come from such biofuels. This could create significant regional economic opportunities – potentially many hundreds of jobs in places like Collie in WA, and Portland and the Latrobe Valley in Victoria.

This exciting, credible opportunity for Australia will not be delivered in 2020, but it can be shaped over the next few years. The hard work must begin now.

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1 Australia's climate conundrum

Australians – and Australian political leaders – broadly understand and support the need to act on climate change. By ratifying the *Paris Agreement*, the Australian Government agreed that all countries must work to limit global warming to well below two degrees Celsius.[1]

But Australia is stuck in a climate conundrum. Political leaders need to balance the national interest – which requires strong global action on climate change – with the legitimate interests of regional communities and workers in carbon-intensive industries, who feel threatened by this action. These 'carbon workers' seem to have rejected the more ambitious emissions reduction targets that Labor took to the 2019 federal election (Figure 1.1).[2]

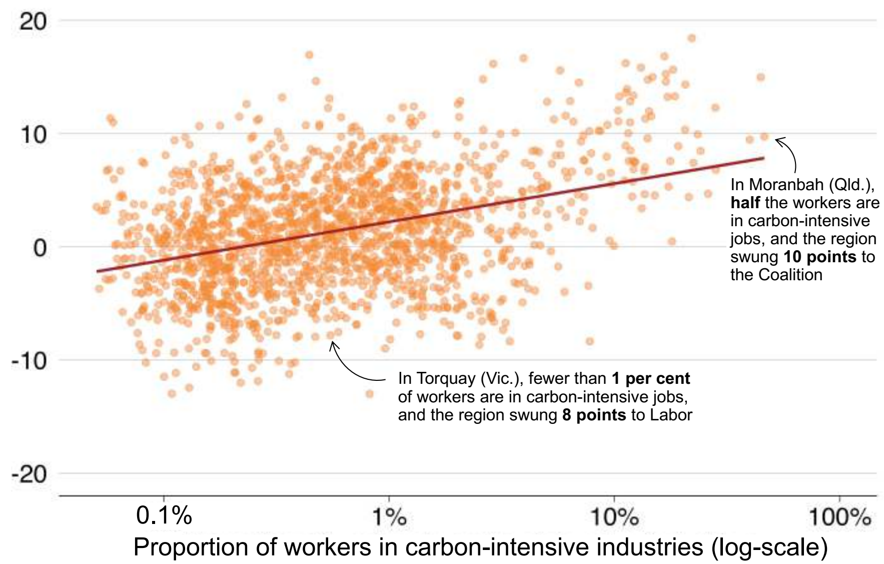
The future of Australia's carbon-intensive industries, particularly coal mining, will be determined primarily in Beijing and New Delhi, not in Canberra. Carbon workers deserve honesty about the ability of Australian governments to protect their jobs. The government's current approach – modest domestic emissions reduction targets – will not effectively protect jobs in the face of global climate action. Nor does it help capture the economic opportunities Australia might have in a decarbonised world. This ultimately works against Australia's national interest.

1.1 Global climate action is in Australia's national interest

Taking action on climate change is hard. It is particularly hard for Australia, as a major exporter of fossil fuels and with high levels of

Figure 1.1: Regions that depend on carbon-intensive industries swung harder to the Coalition in the 2019 federal election

Two-party preferred swing to the Coalition by SA2, percentage points (negative values are swings to Labor)



Notes: 'SA2s' or 'Statistical Areas Level 2' are ABS-defined regions that represent a community that interacts together socially and economically. They usually contain 3,000 to 25,000 people. 'Swing' is the weighted average swing from polling booths within the SA2.

Sources: Grattan analysis of ABS (2017) and AEC (2019).

1. With an aspirational target of limiting warming to 1.5℃ above pre-industrial levels: UNFCCC (2015, Article 2).
2. Labor's policies included a 45 per cent reduction in emissions from 2005 levels by 2030. The Coalition's target was 26-to-28 per cent: Slezak (2019).

emissions per person. But, despite this, global climate action is in Australia's national interest.

This is easily missed in public debate, because the losers from climate action are more visible than the winners, and the costs come sooner than the benefits. Prime Minister Scott Morrison's framing of the issue emphasises the more immediate and tangible costs of action, and ignores the costs of inaction:

> Currently no one can tell me that going down that path [net zero emissions] won't cost jobs, won't put up your electricity prices, and won't impact negatively on jobs in the economies of rural and regional Australia.[3]

This framing perhaps explains why the Australian Government is focused on 'zero cost or low cost' technological solutions for reducing emissions.[4]

But it is an unbalanced framing. Climate change and global climate inaction will have significant costs for Australia. While Australia cannot solve this global problem on its own, an honest debate about the costs of reducing emissions must also acknowledge the costs of not reducing emissions. And it is clear that the consequences of global inaction – the costs of living with several degrees of warming – will be very bad for Australia.

The year 2019 highlighted the costs of inaction on climate change. Australia was 1.5°C hotter than average. Temperature records were set and broken, while rainfall was at its lowest level on record.[5] Bushfires burned unprecedented swathes of Australia during the summer of 2019-20.[6] Drought continued across the Murray-Darling Basin.[7] And over the 2019-20 summer, the Great Barrier Reef suffered its third mass bleaching event in five years.[8]

Recent events reflect longer term trends across Australia's economy and society.

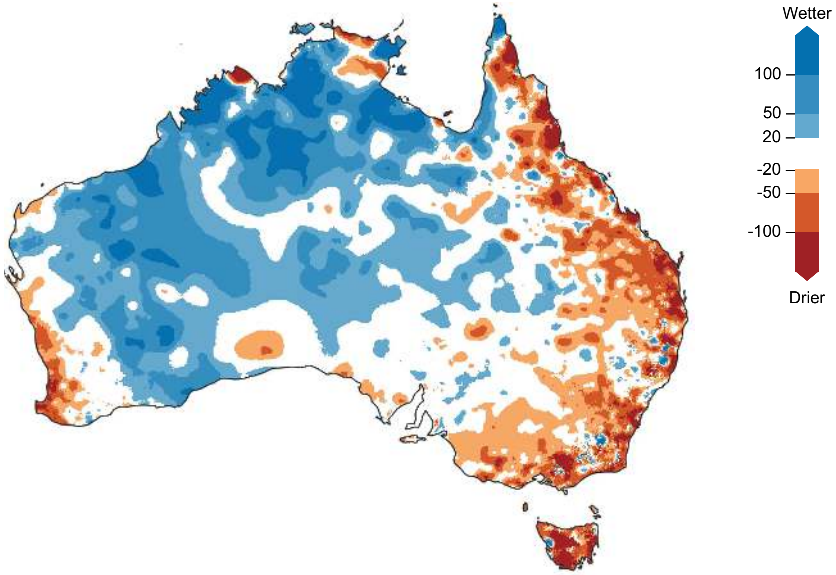
The agricultural sector is already struggling to adapt to a changing climate. Rainfall has declined across the main agricultural regions of eastern Australia (Figure 1.2 on the following page), and this is trimming profits for farmers (Figure 1.3) – by 22 per cent, or $18,600 a year for an average broadacre farm.[9]

The effects were worse for cropping farmers, with average profits down 35 per cent – resulting in $1.1 billion less revenue per year for the cropping industry.[10] 1.5°C of warming will further reduce Australia's farmland productivity, and the effects at 2°C would be worse again.[11]

Parts of the tourism sector are directly threatened by a warming climate. The Intergovernmental Panel on Climate Change (IPCC) warns that 'the Great Barrier Reef is expected to degrade under all climate change scenarios'[12] – bad news for the 35,000 tourism workers who directly depend on it, and the $2.7 billion that its tourist activities add to the Australian economy each year.[13] Alpine regions are

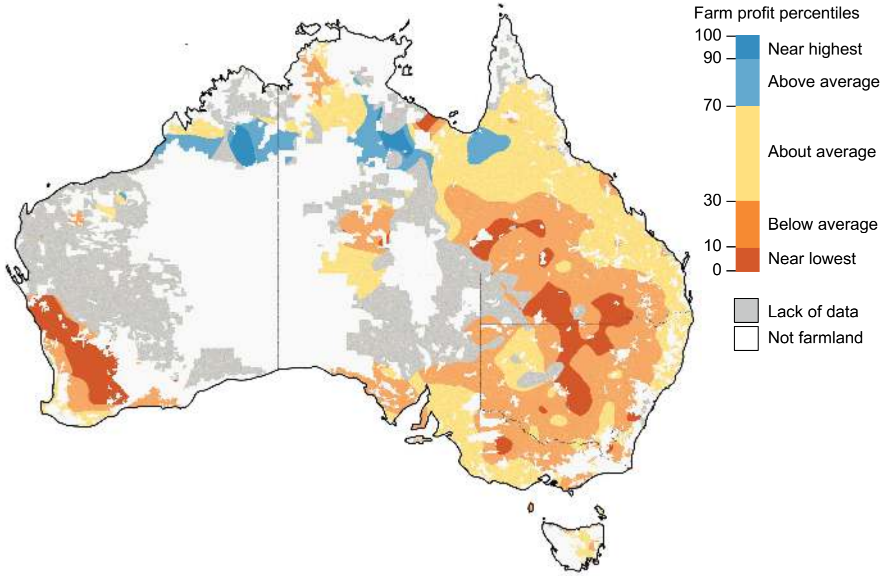
3. Morrison (2020).
4. The Minister for Energy and Emissions Reduction, Angus Taylor, in discussing the Australian Government's Technology Investment Roadmap, has said that 'the goal for each technology is to approach economic parity or better, which means the shift to lower emissions is zero cost or low cost': Major (2020).
5. BOM (2020a).
6. Boer et al (2020).
7. BOM (2019, p. 4).
8. Great Barrier Reef Marine Park Authority (2020) and T. P. Hughes et al (2019). Over 2016-2018, large coral reef systems such as the Great Barrier Reef lost up to 50 per cent of their shallow water corals: Hoegh-Guldberg et al (2018, p. 229).
9. N. Hughes et al (2019).
10. Ibid.
11. Hoegh-Guldberg et al (2018, Table 3.5, p. 250).
12. Reisinger et al (2014, p. 1401).
13. Deloitte Access Economics (2017, p. 69). These figures are the direct contribution only. Another $3 billion of value is generated indirectly through, for example, additional spending at cafes and restaurants. The reef also supports jobs in aquaculture, recreation, and science.

Figure 1.2: The main agricultural regions in Australia's east and south-west have become drier over the past half-century
Change in average annual rainfall (mm) for the 30 years spanning 1986-2015, compared to 1956-1985



Source: Grattan analysis of BOM (2020b).

Figure 1.3: Climate change has already reduced farm profits across large swathes of Australia
Average farm performance in current climate conditions (2000-2019), compared to long-term average (1950-2019)



Source: N. Hughes et al (2019).

expected to suffer as declining snow cover deters skiers.[14] And more frequent heat waves will make the Northern Territory less attractive for tourists due to the risk of heat stress.[15] The possibility of more natural disasters also threatens the industry – the 2019-20 bushfires deprived many regions of their seasonal tourist trade.[16]

Cyclones, storms, and floods cause greater losses for insurers than fires or other disasters – more than 80 per cent of insured losses since 1980.[17] Over the past decade, these disasters caused insured losses in Australia of at least $20 billion.[18] And a warmer climate will increase the intensity of heavy rainfall events, even in areas expected to receive less rain on average.[19]

Flooding and cyclones regularly disrupt the mining industry too;[20] these risks could rise with more intense rainfall.[21] And water availability is also a concern, with large miners unable to rely on their existing water licenses during prolonged drought.[22]

The overall picture is bleak for asset owners in a warmer climate. An uptick in the frequency and severity of natural disasters will raise insurance premiums and make some assets effectively uninsurable.[23] An increasing share of homeowners will feel the pinch; more than 5 per cent of properties are expected to face annual weather-related insurance premiums costing more than 1 per cent of the property's value by 2030.[24]

And the health effects are worrying too. A warmer climate means more heat waves: these directly threaten lives, and force workers in occupations such as mining and farming to sacrifice productivity for their safety.[25] And extreme weather threatens mental and physical wellbeing. For instance, Australians affected by bushfires have higher rates of mental health problems over the long term,[26] and bushfire smoke causes more people to go to hospital with respiratory-related problems.[27]

Climate change poses risk across the Australian economy. It's unsurprising that the governor of the Reserve Bank, Philip Lowe, has warned that the 'economic implications [of climate change] are profound', and are already affecting Australian investment decisions and exports.[28]

1.2 Climate action threatens the interests of some Australians

Climate action is in the broad national interest, but some Australians do not agree. Understandably, the people who live in regions that are home to large fossil-fuel extracting and emissions-intensive industries may have a different view on climate action than those living in the rest of the country.

Australia has close to 100,000 'carbon workers' (see Box 1 on the next page). About half of these carbon workers are concentrated in particular geographic areas (Figure 1.4 on page 10).

14. Reisinger et al (2014, p. 1401).
15. Ibid (p. 1401).
16. Tourism Australia (2020).
17. Grattan analysis of Munich Re (2020a) and Munich Re (2020b).
18. Grattan analysis of Insurance Council of Australia (2020).
19. BOM and CSIRO (2018, pp. 3, 8).
20. In March 2017, Tropical Cyclone Debbie damaged key rail infrastructure in the Bowen Basin of Queensland, halving Australia's metallurgical coal exports in April: Cunningham et al (2019).
21. Reisinger et al (2014, p. 1399).
22. Ker (2019).
23. Reisinger et al (2014, p. 1403).
24. Steffen et al (2019, pp. 6–7). The authors of that study argue that premiums above this threshold are effectively unaffordable.
25. Hanna et al (2011).
26. Duckett et al (2020, p. 8).
27. Ibid (p. 7).
28. Durkin (2020).

Box 1: What is a 'carbon worker'?

This report frequently refers to 'carbon workers'. These are Australians working in carbon-intensive industries such coal mining, oil and gas extraction, fossil fuel electricity generation, cement manufacture, and 'integrated steel-making' using blast and basic oxygen furnaces.[a]

We include integrated steel-making because it is inherently emissions-intensive – coal is a primary input, and carbon dioxide is a major byproduct of the process. This is in contrast to steel-making using an electric arc furnace, which can easily switch to zero-emissions electricity. Manufacture of cement clinker is inherently emissions-intensive due to the heating of limestone (calcination), which releases carbon dioxide.

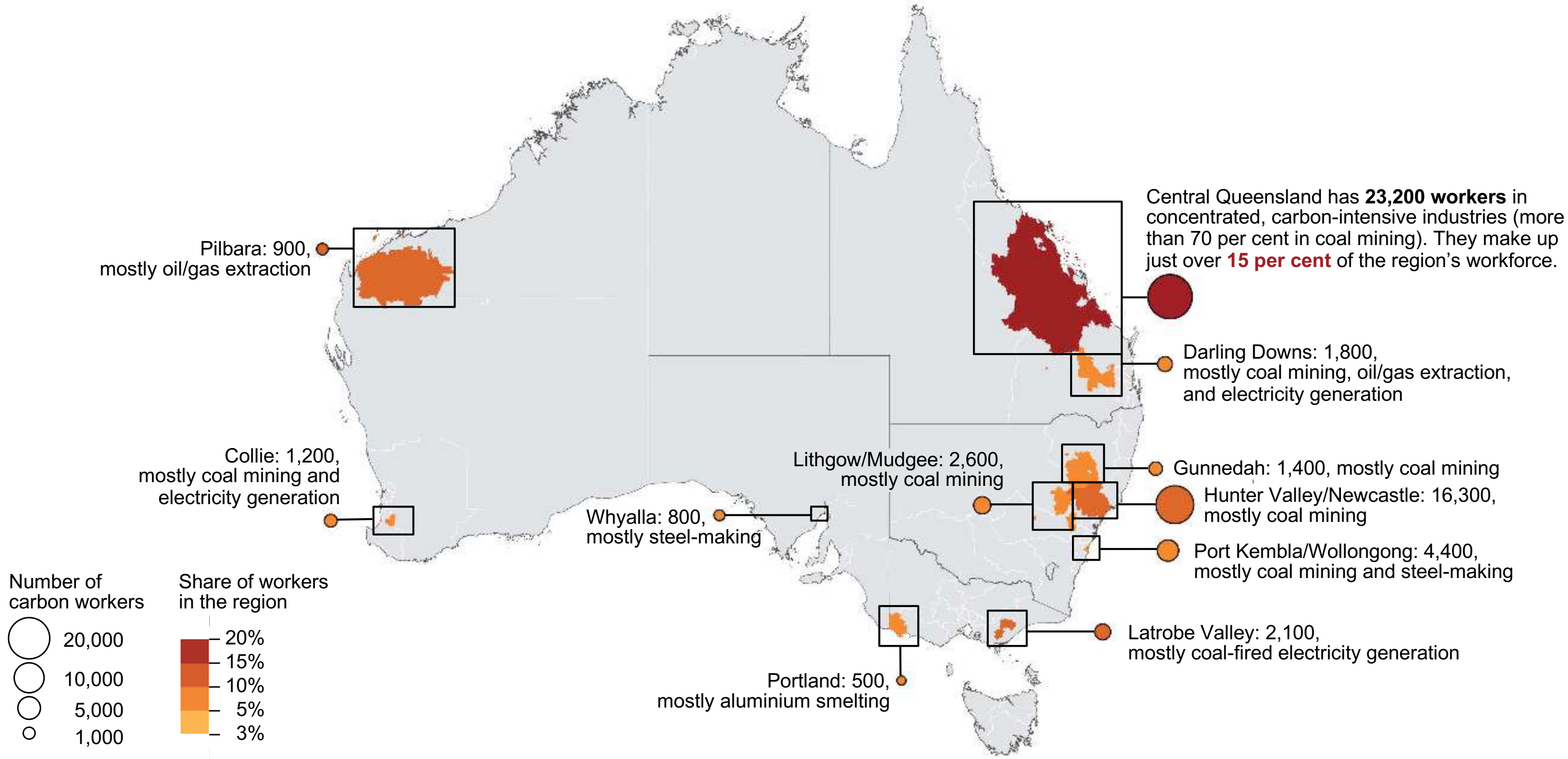
We have not defined workers in all energy- or electricity-intensive industries as carbon workers. This is because fossil fuel energy sources can generally be substituted for low-emissions energy sources. We made one exception: aluminium smelting. Aluminium smelting is vastly more electricity intensive than any other large-scale industrial process,[b] and its need for constant electricity makes a transition to low-emissions electricity particularly difficult in places that do not have abundant hydroelectricity. Also, the electrolytic aluminium smelting reaction has traditionally relied on carbon anodes, which release carbon dioxide as they are used.[c]

Workers in land-use, agriculture, or transport sectors are generally excluded, though each sector significantly affects Australia's emissions.[d] Land-use – such as clearing or replanting forests – can be either a source or sink of emissions, and so is not inherently emissions-intensive. Meat and Livestock Australia, the research and marketing body for the red meat industry, has committed the industry to be carbon neutral by 2030.[e] And the prospects for decarbonising transport, such as through electrification, are good. But we have included port and rail workers in regions with a significant number of coal workers, because many of these jobs directly depend on the coal industry.

a. In the 2016 Census, employed people are matched to an industry according to the Australian and New Zealand Standard Industrial Classification (ANZSIC). The following industries were deemed carbon-intensive: Coal Mining, Gas Supply, Oil and Gas Extraction, Fossil Fuel Electricity Generation, Cement and Lime Manufacturing, Aluminium Smelting, Petroleum Refining and Petroleum Fuel Manufacturing, Petroleum Exploration, and Other Petroleum and Coal Product Manufacturing. Integrated steel-making is also included – these worker numbers were determined separately from Census data – but steel recycling in electric arc furnaces was not. If at least 1.5 per cent of workers in an SA4 (an ABS-defined region usually containing 100,000 to 500,000 people, and representing a labour market) worked in Coal Mining, the following ANZSIC codes were also deemed carbon jobs: Mining and Construction Machinery Manufacturing, Lifting and Material Handling Equipment Manufacturing, Other Mining Support Services, Water Transport Support Services, Water Freight Transport, and Rail Freight Transport.
b. Daley and Edis (2010, p. 9).
c. 'Inert' anodes offer a carbon-free alternative; these are being developed and commercialised internationally: Rio Tinto (2018).
d. Ha (2019).
e. MLA (2020).

Figure 1.4: A number of Australian communities have significant concentrations of carbon workers

Working-age, employed residents in regionally-concentrated, carbon-intensive industries (as of 2016 Census)



Notes: Worker numbers are determined from the population aged 18-65 in the 2016 Census. The ABS has divided Australia into more than 2,000 statistical areas known as 'SA2s'. An SA2 represents a community that interacts together socially and economically, usually containing 3,000 to 25,000 people. Each SA2 in Australia was classified according to whether it contains regionally-concentrated carbon workers. SA2s sit within larger areas called SA3s, which sit within even larger areas called SA4s. Carbon workers in each SA2 were deemed regionally-concentrated if at least 5 per cent of workers at the SA2 level – or at least 3 per cent at either the SA3 or SA4 level – worked in carbon-intensive industries. SA2s with fewer than 100 carbon workers are not shown. Iron and steel smelting job estimates were not taken from the Census, but instead from Grattan estimates of the steel-making jobs present in Whyalla and Port Kembla, calibrated to a benchmark of 500 jobs per million tonnes of rated capacity based on IEA Environmental Projects (2013, Section E, pp. 27-28). This was done to exclude jobs in less carbon-intensive fabrication activities that were captured within the iron and steel smelting category. A small number of aluminium smelting jobs near Bell Bay and George Town in Tasmania were excluded given the availability of zero-emissions hydroelectricity in that state.

Source: Grattan analysis of ABS (2017).

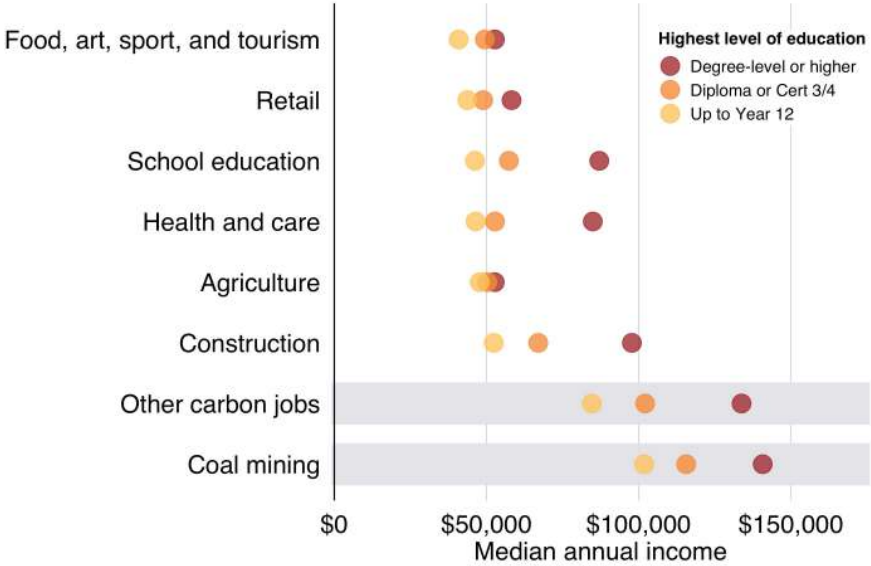
The largest clusters are in the major coal mining regions of central Queensland and the Hunter Valley, which are also home to power stations and metal smelters. Smaller coal mining regions are located in NSW – in the vicinity of Port Kembla, Lithgow, and Gunnedah – and to supply coal-fired power stations in Collie in WA and the Latrobe Valley in Victoria. Port Kembla in NSW and Whyalla in SA are home to emissions-intensive steelworks, and Portland in Victoria hosts an aluminium smelter. Oil and gas workers are primarily concentrated in the Pilbara in WA and the Darling Downs in Queensland.

This report focuses on Australia's 55,000 geographically-concentrated carbon workers, and the 'carbon-intensive regions' they live in. These workers face more acute social and economic challenges than carbon workers distributed across the rest of Australia. Metropolitan carbon workers will have access to a much greater range of job opportunities. And many of those are managers and professionals, and will more easily transfer their skills to new jobs. If coal mining declines, a mining executive in Brisbane will have access to many more new opportunities than a machinery operator in central Queensland.

Geographic concentration compounds the challenges facing each individual worker. If geographically-concentrated industries shed workers, those workers will face strong competition from their former workmates to win a new job. And they would have to take a pay cut to find a new job close to home – existing carbon jobs pay far more than other jobs in the same location (Figure 1.5).

Given these challenges, it is understandable that people who live in central Queensland, the Hunter Valley, Port Kembla, Whyalla, Collie, and Portland might vote against action on climate change, if it is seen to threaten their jobs. The Labor Party took a more ambitious emissions reduction target to the 2019 federal election – a target of 45 per cent below 2005 levels by 2030, compared to the Coalition's target of 26-to-28 per cent.[29] Communities with higher proportions of carbon workers appear to have rejected Labor's policy platform, and swung more strongly to the Coalition (Figure 1.1 on page 5).[30] These workers were largely concentrated in just five electorates and

Figure 1.5: Jobs in carbon-intensive industries pay well
Median annual income by highest level of education, in areas with a high proportion of carbon jobs



Note: Incomes are in 2016 dollars, derived from responses to the 2016 Census.

Source: Grattan analysis of ABS (2017).

29. Slezak (2019).
30. There are many factors that affect how people vote in an election, and it is difficult to draw firm conclusions without surveying large numbers of voters or performing statistical analysis that takes account of a range of factors. For a detailed explanation of other factors influencing the 2019 election, see Emerson and Weatherill (2019) and Cameron and McAllister (2019). We have not attempted to perform this analysis, because this report does not aim to explain the results of the 2019 election, nor provide strategic advice for parties in future elections.

were unlikely to have changed the result in any one of those – but they illustrate the tension climate policy creates between regional and national interests.

This is despite Labor's attempts to assuage these workers' fears with a policy for a 'just transition'.[31] The policy aimed to assist communities that will be affected by future closures of coal-fired power stations, by mandating pooled redundancy schemes, for example. It seems that either the message was poorly delivered or voters did not trust Labor to manage such economic risks.

1.3 Balancing regional and national interests

Australia's climate conundrum is balancing the national interest – which requires strong global action on climate change – with the legitimate interests of regional communities and carbon workers who feel threatened by this action.[32] The Minister for Energy and Emissions Reduction, Angus Taylor, is acutely aware of this challenge:

> Australia must do its bit to reduce emissions to address climate change, and we are doing our bit. But we must do it in a way that secures our way of life – not just the way of life in inner Sydney, but the way of life in Newcastle, in Roma, and in Townsville.[33]

It is not unusual for governments to have to balance the interests of the community overall and those of particular regions or interest groups. Public policy is rarely win-win; some groups are often made worse off to benefit the wider community. Similarly, the interests of carbon workers do not override those of other Australians – a balance must be struck.

31. Australian Labor Party (2019).
32. This is not the only balancing act in Australian climate policy; the federal Coalition Government must also contend with the legacy of the climate wars, political ideology, and pressures from other voters, businesses, and party members: Wood (2020).
33. Taylor (2020).

Irrespective of how Australia tries to balance these competing interests, the future of Australia's carbon workers will not be determined in Canberra. It will be determined in China, India, and Australia's other major Asia-Pacific trading partners. Three-quarters of coal mined in Australia is exported.[34] Australia has ridden a coal boom that was, primarily, made in China – the number of people employed in coal mining increased by about 70 per cent between 2006 and 2016.[35] If our major trading partners move away from coal, we will have to ride the rollercoaster back down. It's a similar story for natural gas. This means that domestic emissions-reduction policies can do little to extend the long-term viability of carbon-intensive industries.

The future of the coal industry is also highly uncertain. Scenarios developed by the International Energy Agency indicate large differences in global coal demand, depending on whether countries take the necessary actions to limit warming as agreed in the Paris Agreement (Figure 1.6 on the next page). This uncertainty is compounded by how importing countries will respond to changing market circumstances – for example, India's Minister of Coal and Mines, Pralhad Joshi, has openly discussed a move away from imported thermal coal.[36]

The future of gas depends on how cheaply emissions can be captured and permanently stored. In the absence of large-scale carbon capture and storage, demand for gas needs to fall from the late 2020s to meet the Paris Agreement.[37]

Australian governments need to be honest with carbon workers: continuing attempts to protect carbon jobs from global forces will ultimately fail. Leaders from both sides of politics in Australia have asserted that we will and should continue to export carbon-intensive

34. Cunningham et al (2019). For black coal, the proportion is closer to 85 per cent.
35. ABS (2017).
36. Singh (2020).
37. IEA (2019a, pp. 178–183).

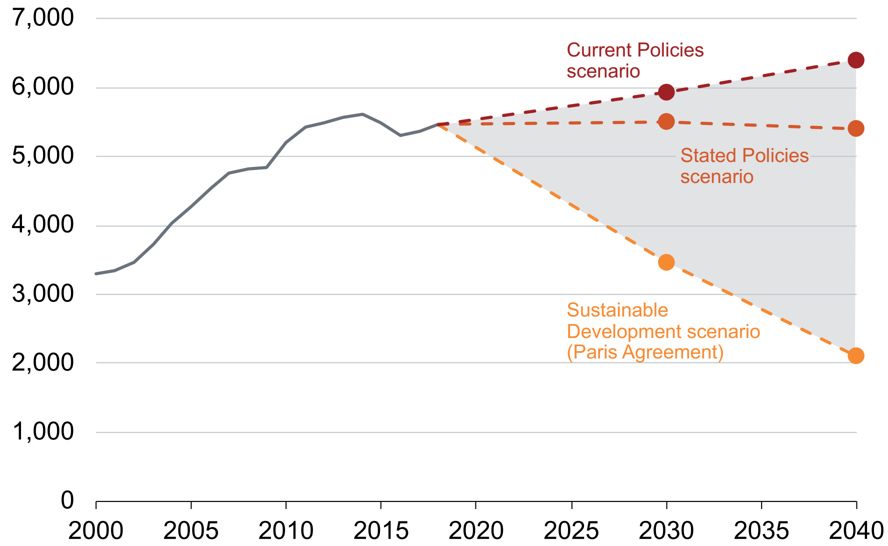
products for decades, while also committing to the Paris Agreement.[38] In reality the future – both for Australian carbon workers and for global decarbonisation – is much less certain.

As well as honesty, Australia's carbon workers would benefit from realistic government strategies that can cope with a range of outcomes. Assuming that coal exports will continue indefinitely is a high-risk strategy. A better approach is economic diversification, particularly into new industries based on zero-emissions energy. Clean energy industries provide Australia with a valuable hedge in an uncertain world. Our fossil fuel resources will be less valuable if the world moves to reduce its emissions, but our renewable energy resources will be more valuable. And those renewable energy resources, as important as they are for Australia, could be even more important for the future of Australia's carbon workers.

The remainder of this report examines Australia's clean energy opportunities, and what they mean for regions with large numbers of jobs in carbon-intensive industries. Chapter 2 looks at the potential ways Australia could exploit its renewable energy endowment. Chapter 3 examines whether these opportunities could be economically viable and support similar numbers of jobs in places that currently host carbon-intensive industries. And Chapter 4 provides targeted recommendations for federal and state governments to ensure Australia is as well placed as possible to capture these opportunities.

Figure 1.6: The future of coal is highly uncertain, leaving Australia very exposed to international trends

Forecast global coal demand, Mtce



Notes: 'Mtce' is million tonnes of coal-equivalent. The 'Stated Policies' scenario takes into account existing policy frameworks and announced policy intentions from countries around the world. The 'Sustainable Development' scenario shows what level of action is required to have a two-thirds chance of limiting global warming to 1.8°C, equivalent to the Paris Agreement's goal of 'well-below' 2°C. The scenarios modelled may no longer be accurate due to the economic shock caused by COVID-19.

Source: IEA (2019b) and IEA (2019a, p. 222).

38. See, for example, Shanahan (2017), Albanese (2020), Parkinson (2018) and Ludlow (2018).

2 Australia's clean energy opportunity

Australia is a major fossil-fuel exporter, so a global move to use low- or zero-emissions energy would present challenges. But it would also present opportunities. Rapid reductions in the cost of wind and solar power over the past decade have turned Australia's large, sunny, and windy land mass into a globally significant resource. A decarbonising world will enable Australia to diversify beyond its existing carbon-intensive industries, by exporting renewable energy – either as electricity or hydrogen – or low-emissions energy-intensive commodities, such as metals, chemicals, and biofuels.

Of Australia's clean energy opportunities, the largest and most economically viable appears to be using renewable hydrogen to produce 'green' (near zero emissions) steel. With globally cost-competitive hydrogen, it will be cheaper to produce green steel here than to ship hydrogen and iron ore to countries such as Japan or Indonesia that have inferior renewable resources. There are also attractive, but probably smaller, opportunities for Australia in producing biofuels, renewable ammonia, and hydrogen, and by exporting electricity via undersea cables.

These opportunities are not certain and will generally rely on either international policies to reduce emissions, or customers being willing to pay a 'green premium'. But these opportunities are credible, particularly if the world moves away from fossil fuels.

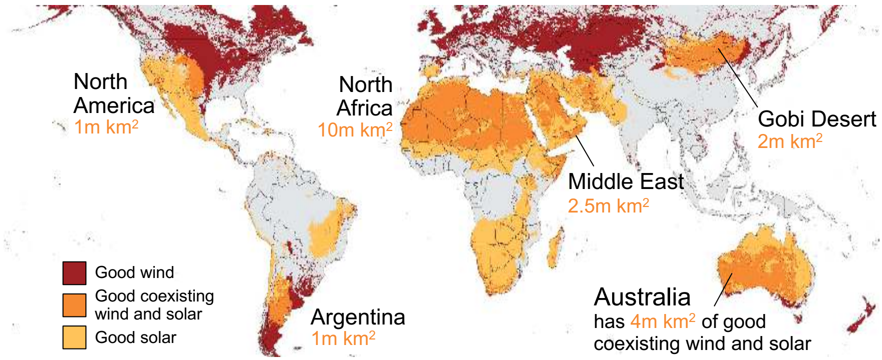
2.1 Australia's renewable resources are large...

Many places in the world have strong wind – especially offshore – or good solar radiation. But few places have as much good-quality solar and onshore wind as Australia (Figure 2.1).

Renewable technologies have become cheap to deploy over the past decade, but it remains relatively expensive to 'firm' solar and wind to provide a constant electricity supply.[39] Energy storage solutions such as batteries and pumped hydro systems contribute significantly to the cost of delivering relatively stable electricity.

But Australia's combination of wind *and* solar resources is likely to give it an energy-cost advantage in a decarbonised world – combined solar and wind partly smooths the natural variations of each individual resource, reducing storage requirements and lowering electricity costs.

Figure 2.1: Australia's renewable energy resource endowment is both large and rare, giving us a comparative advantage
Locations with high-quality onshore wind and solar



Notes: Land higher than 3,000 metres is excluded because renewable energy resources are harder to use when they are in mountainous terrain. High-quality resources are defined to be areas with average wind power-density of at least 450 W/m² and average daily solar photovoltaic potential of at least 4.5 kWh/kWp. North Africa includes the Horn of Africa.

Sources: Grattan analysis of Global Wind Atlas (2020), Global Solar Atlas (2020) and U.S. Geological Survey and National Geospatial-Intelligence Agency (2010).

39. IRENA (2019, p. 12); and Graham et al (2020, p. 24).

This large resource alone does not guarantee Australia's future as an energy powerhouse. Other factors contribute to the cost of renewable electricity: engineering, labour, and transport costs are each likely to be higher in Australia than many other countries. Economies of scale can bring down costs, but Australia's electricity market is relatively small in terms of demand – supplying Australia's domestic needs alone would barely take advantage of the vast renewable resources or the possible economies of scale.

2.2 . . . so we should look to export

Australia's renewable resources cover millions of square kilometres. Not all countries are so lucky. If the world acts decisively to limit carbon emissions, countries with poor renewable resources will have higher energy costs than Australia. They will look to import energy, or energy-intensive commodities, from renewable-rich countries such as Australia. In such a world, Australia's trading partners will either be implementing policies that make emissions-intensive commodities more expensive, or they will be willing to pay a 'green premium' for low-emissions commodities. In either case, Australia is likely to be highly competitive in a range of low-emissions commodity markets.

Harnessing Australia's renewable resources to serve an export market could make this country an energy 'superpower'. This idea has attracted significant attention in recent years.[40]

Building an export industry can create many jobs. Australia's existing energy and mineral industries are evidence. Jobs in coal increased by 70 per cent between 2006 and 2016 as Australia ramped up its exports.[41] And more than twice as many Australians are employed in oil and gas extraction today compared to 2006, because of the dramatic expansion of the LNG industry.[42] Jobs in iron ore mining quadrupled over the decade as Australia's production tripled to satisfy growing demand in China.[43]

Simply producing clean energy does not create many jobs, even if the energy is exported. It takes only 10-to-20 full-time staff to manage a 400 MW wind farm, compared to hundreds of short-term jobs involved in construction.[44] Building enough renewable generation to meet demand in Australia's National Electricity Market, while reducing emissions in line with the Paris 2 °C target, would require thousands – but not tens of thousands – of ongoing wind and solar jobs.[45] And on average, these jobs don't pay as well as current fossil-fuel electricity generation jobs.[46]

Many more jobs are likely to come from Australia using its energy cost advantage to produce low-emissions, energy-intensive commodities for export. Manufacturing activities are typically more labour-intensive than renewable energy operation, and are likely to have conditions and pay more like today's jobs in smelting and coal power stations.

40. Garnaut (2019) used the term superpower in this way in his recent book, and his thinking has greatly informed this report. Chief Scientist Alan Finkel considers that Australia can use its renewable resources to become a hydrogen export 'powerhouse': COAG Energy Council (2019, p. v). And Ueckerdt et al (2019) have analysed scenarios involving large-scale hydrogen and energy-intensive commodity exports.

41. ABS (2017). Coal exports rose significantly over this decade: Cunningham et al (2019).
42. ABS (2017); and Percival (2019, Figure 2).
43. ABS (2017); and Summerfield (2018).
44. The 453 MW Cooper's Gap wind farm in Queensland, for example, is expected to create up to 20 ongoing jobs, and up to 200 short-term jobs during the peak of construction: AGL (2020).
45. Calculations based on ongoing jobs needed for an additional 21,000 MW of wind and 25,000 MW of solar, consistent with the 'Step Change' scenario of the draft 2020 Integrated System Plan: AEMO (2020); assuming 0.04 full-time equivalent (FTE) jobs per MW of wind capacity and 0.02 FTE jobs per MW of solar capacity for large-scale facilities (see Table A.7 on page 47). Smaller facilities will probably require a higher ratio of jobs.
46. Grattan analysis of ABS (2017).

2.3 How Australia can export its renewable resources

Australia can export its renewable resources in a number of ways. One is to build underwater electricity cables to neighbouring countries. Another is to use renewable electricity to make hydrogen, and then export the hydrogen as an 'energy carrier'. A third way is to make energy-intensive commodities for export. This third approach looks the most likely to create large-scale, economically feasible opportunities for Australia.

2.3.1 Direct export by undersea cable

Undersea cables are a proven way to transport electricity over several hundred kilometres.[47] But for Australia to export electricity to large-electricity consuming neighbours such as Indonesia, we would need cables that run underwater for several thousand kilometres.

These exports would face significant technical and operational challenges. Customers and generators would need to be satisfied that the risk of prolonged outages could be managed.[48] And very long undersea cables cost a lot.

Despite this, two Australian projects have proposed large-scale, long-distance power transmission cables from northern Australia to other countries. The Asian Renewable Energy Hub has proposed building a cable from Eighty Mile Beach in WA's Pilbara region to Indonesia.[49] And the Sun Cable project plans to export solar power from Tennant Creek in the NT to Singapore via a 3,800 kilometre cable.[50]

47. In Australia, the Basslink cable has transferred power between Tasmania and Victoria since 2006. Similar cables are used in Europe, North America, Japan, New Zealand, the Republic of Korea, China, and the Philippines.
48. For example, Basslink suffered a six-month outage between December 2015 and June 2016, causing significant problems for Tasmania's energy supply.
49. NS Energy (2020). Recently it has given priority to producing hydrogen for export.
50. Sun Cable (2020).

Projects of this kind may ultimately prove successful, but the risks and market uncertainties suggest that direct undersea exports will be small relative to Australia's other potential clean energy opportunities.

2.3.2 Hydrogen exports

In 2019 the COAG Energy Council developed a National Hydrogen Strategy, led by Chief Scientist Alan Finkel.[51] This strategy focused heavily on the potential for Australia to export low-emissions hydrogen (Box 2) to meet the energy needs of Asian trading partners.

Box 2: What is 'low-emissions hydrogen'

Low-emissions hydrogen can be produced in two main ways. One is to use low-emissions electricity, most likely solar and wind power, to power a machine called an 'electrolyser' that splits water into its constituent parts – hydrogen and oxygen. This is known as renewable or 'green' hydrogen.

The other is to gasify coal or 'reform' natural gas to produce a mix of hydrogen and carbon dioxide, and then capture and store the carbon dioxide. This is sometimes called 'blue' hydrogen.

If large-scale hydrogen exports came about, Australian renewable energy would warm homes, fire cook-tops, feed industrial processes, and power vehicles in other countries, just as Australia's fossil fuel exports do today.

But the market for large-scale hydrogen exports does not exist today, and its prospects are uncertain. Hydrogen is hard to transport – it must either be liquefied by cooling to minus 253℃, or converted into a chemical such as ammonia. To make exports viable despite the high

51. COAG Energy Council (2019).

cost of transport, Australian hydrogen would need to be substantially cheaper than that made in other countries.

The National Hydrogen Strategy acknowledges the uncertainty of future growth in the hydrogen market. Modelling done in support of the strategy considered a range of scenarios with very large differences in the level of demand for hydrogen.[52]

In future Australia may well successfully export hydrogen to energy-poor countries in Asia, but the uncertainties mean that it is unlikely to be Australia's most significant clean energy opportunity.

2.3.3 Export of energy-intensive commodities

An alternative to exporting renewable electricity by cable or green hydrogen by ship is for Australia to use its renewable resources to make low-emissions, energy-intensive commodities for export. This can involve both attracting new industries to Australia, and maintaining or expanding existing energy-intensive industries while transitioning them from fossil to renewable energy.

Table 2.1 on the following page summarises Australia's prospects for supplying seven energy-intensive, globally-traded commodities in a future decarbonising world. The seven commodities are steel, cement, aviation fuel, shipping fuel, aluminium, ammonia, and alumina.[53]

'Green steel' (Box 3 on page 19) looks to be Australia's largest low-emissions export opportunity. Steel is the largest of these seven markets today by value, and this is likely to remain true in 2050, despite increased recycling reducing demand for new 'ore-based' steel.

Australian-made green steel also has particularly good economic prospects. As with any long-term analysis, the conclusions in this report are uncertain, but they are robust across a range of assumptions and scenarios. Australia's abundant solar and wind resources are well suited to making hydrogen (Section 2.4.1), the key energy input to making green steel from renewable energy. And Australia's lower-cost green hydrogen will make it a better place to produce green steel than places such as Japan or Indonesia (Section 2.4.3).

No doubt Australia will confront technical (Section 2.5.1) and economic (Section 2.5.2) challenges. But the analysis in this report suggests that the green steel opportunity is both large enough and economically credible enough to justify policy action.

Australia's opportunities in other low-emissions commodities are either smaller or more constrained. For example, making low-emissions cement depends more on capturing and storing carbon dioxide than on the cost of renewable energy. Australia does not have a clear competitive advantage in carbon capture and storage, and the high cost of transporting this bulky commodity further limits Australia's ability to win a large share of the global cement market.

Australia's ability to export biofuels for aviation or shipping is likely to be limited by the local availability of biomass.[54] Australian biofuel production may well provide important economic opportunities for a number of carbon regions (see Section 3.7 on page 33), but it is unlikely to become globally significant.

52. Deloitte (2019, pp. 4–5).
53. The steel market examined covers only new 'ore-based' steel. Recycled steel is much less energy and emissions-intensive than ore-based steel (see Box 3 on page 19). Coal and liquefied natural gas are not considered because they cannot be easily decarbonised. Road transport fuels are not considered because the rapidly falling cost of batteries means that road transport will probably use electricity or hydrogen, rather than a decarbonised liquid fuel. By contrast, planes' and ships' large fuel needs and very long travel distances make using electricity or hydrogen difficult, and make the use of a decarbonised liquid fuel, such as biofuel or ammonia (in the case of shipping), more likely: ETC (2018e, p. 19).
54. ETC (ibid, p. 121) indicates that Australia has far less biomass than many other parts of world, including Europe, Russia, and both North and South America.

Table 2.1: Steel is the largest clean manufacturing opportunity for Australia in a low-carbon world

Industry	Current approach	Share of global emissions	Current market size (US$b)	Future (low-emissions) approach	2050 market size (US$b)	Key advantage	Key disadvantage
Steel (ore-based only)	Coal is used in a blast furnace to smelt iron ore to iron metal, releasing CO_2. Iron metal is refined to steel using oxygen	7.0%	660	Low-emissions hydrogen is used to reduce iron ore to iron metal, releasing water. Iron metal is refined to steel using electricity	590	Hydrogen complementary to wind and solar	Technology not yet proven at commercial scale
Cement	Limestone calcined (heated) to produce clinker, releasing carbon dioxide	4.5%	490	Calcination emissions captured and stored. Low-emissions heat sources replace fossil energy	540	Hydrogen can be used for calcination	Limited carbon storage resources in Australia
Aviation	Fossil based fuel (primarily kerosene) used as jet fuel	1.9%	160	Biofuels made from non-food biomass ('second generation' biofuels)	230	Biofuels can be used in existing engines	Biomass limits
Shipping	Fossil based fuel (primarily heavier fuel oils) used as shipping fuel	2.2%	110	Second generation biofuels or low-emissions ammonia	180	Biofuels can be used in existing engines	Biomass limits/ difficult transition to ammonia
Aluminium	Electricity (of various sources) used to smelt alumina (refined bauxite) into aluminium	1.4%	70	Low-emissions electricity used in existing process	130	No technical challenges	Firming costs disadvantage Australia
Alumina	Fossil fuels are used for process heat to refine bauxite to alumina	0.2%	60	Low-emissions heat sources replace fossil energy in the existing process	110	Australia has good prospects for low-emissions heat	Very small market
Ammonia	Hydrogen is extracted from fossil fuels (gas or coal) and combined with nitrogen (from the air)	0.8%	60	Low-emissions hydrogen replaces fossil-based hydrogen in existing process	100	Hydrogen complementary to wind and solar	Economics of clean production will need to improve

Notes: Market value is the price of a commodity multiplied by the volume sold, rounded to the nearest US$10 billion. Market value now and in 2050 are both estimated based on average market prices over the period 2015 to 2019 inclusive, in 2019 US dollars. Market size in 2050 is indicative only, because prices will change over time. Steel market value is based on ore-based steel only (i.e. it excludes recycling of scrap steel). To avoid double-counting, the value of the aluminium market excludes the value of the alumina input. Commodities are ordered by current market size. Current production volumes are for 2018 and are based on: World Steel Association (2019), IATA (2019), IMO (2014), IEA (2019c) and USGS (2020a). 2050 production volumes are based on: ETC (2018a), ETC (2018b), ETC (2018c), ETC (2018d) and European Aluminium (2019); and an extrapolation of long-run growth rates for ammonia using USGS (2020b). Market prices are based on: Steel Benchmarker (2019), Fearnleys (2020), US Energy Information Administration (2020) and USGS (2020a). Emissions are based on: World Steel Association (2018), ETC (2018b), IEA (2019d), World Aluminium (2020a), World Aluminium (2020b) and Giddey et al (2015). World emissions include all greenhouse gases, and all sources except land use, land use change, and forestry, using World Resources Institute (2018) and IEA (2019e).

Source: Grattan analysis based on the sources cited above.

Australia already exports aluminium, a particularly electricity-intensive commodity. There is no technical barrier to Australia exporting aluminium produced using solar and wind power, but these intermittent renewable resources would need to be firmed to provide a constant electricity supply. Firming electricity is generally more expensive than firming hydrogen, and this means that Australia is likely to be better suited to producing green steel than green aluminium (Section 2.4.1). And the aluminium market is much smaller than the steel market.[55]

Ammonia is an industrial chemical made of hydrogen and nitrogen. Australia's renewable resources can readily supply the green hydrogen needed to make low-emissions ammonia. But ammonia does not offer the opportunity green steel does. The market is much smaller (Table 2.1) and the economics are more challenging – until hydrogen costs fall substantially, green ammonia will cost more relative to fossil-based production than green steel (Section 2.4.2). Ammonia could be adopted as a low-emissions shipping fuel, significantly increasing the potential market size, but other fuel options – such as the use of hydrogen or biofuels – make this quite uncertain.

Finally, Australia has good prospects to remain a significant exporter of alumina, the refined chemical compound used to make aluminium. In future Australia could produce low-emissions alumina using hydrogen for high-temperature heat, and solar thermal energy or electricity for lower-temperature heat.[56] But the alumina market is much smaller than the steel market – Australia's primary opportunity here is to retain existing jobs through a successful transition from fossil to renewable energy, rather than creating new jobs.

55. Market value calculations in Table 2.1 net out the value of the alumina input, to avoid double-counting.
56. ARENA (2019, pp. 81–83).

Box 3: What is 'green steel'?

Steel is a refined form of iron metal. Making it produces large quantities of greenhouse gas emissions, primarily from the use of coal as a 'reductant' – the carbon in coal reacts chemically with the oxygen in iron ore, leaving iron metal and carbon dioxide.

Steel is also made using natural gas instead of coal, in a process known as 'direct reduction'. This involves splitting natural gas into a mix of carbon monoxide and hydrogen, and using these gases to reduce iron ore to iron metal. Gas-based direct reduction roughly halves the carbon dioxide emitted per tonne of steel.

But lower-emissions steel is still not 'green steel'. For this you need a carbon-free reductant. The best candidate is pure hydrogen – using it to make steel leaves only water as a byproduct.

Other very low emissions steel-making techniques are possible, such as gas-based direct reduction with carbon capture and storage.

It is relatively easy to make low-emissions recycled steel from scrap. No reductant is required, and so the main source of emissions is the electricity used to melt the steel (in an 'electric arc furnace'). Even using coal-based electricity, recycled steel produces about one quarter of the emissions of new 'ore-based' steel made using coal.

But steel scrap is not widely available. To tackle climate change, the world will need large volumes of decarbonised ore-based steel over coming decades. For this reason, this report focuses on low-emissions ore-based steel-making.

Appendix A.1 provides more detail on steel-making processes.

2.4 Australia is well placed to make green steel

2.4.1 Hydrogen storage balances intermittent wind and solar

Australia's abundant, but intermittent, wind and solar resources are better suited to making hydrogen-intensive commodities such as green steel than electricity-intensive commodities such as aluminium.

The electrolysers that make hydrogen are flexible – they can turn on and off in response to the availability of renewable electricity. This, plus the relatively low cost of storing hydrogen (Box 4), means that hydrogen can be produced when energy is abundant and stored for when it is scarce. Hydrogen storage acts as a buffer between an intermittent renewable energy supply and the continuous steel-making process.

Aluminium smelters cannot turn on and off in the same way as electrolysers – if they turn off for more than a few hours, the molten aluminium freezes and damages the smelter. This means that batteries or other forms of electricity storage must act as the buffer between the intermittent wind and solar electricity and the continuous smelting process. This is technically achievable, but more expensive than hydrogen storage.

These factors mean that countries such as Australia with abundant solar and wind resources will be better suited to making hydrogen-intensive commodities such as green steel. Countries with low-cost hydroelectricity – which is not intermittent – will be better placed to make low-emissions aluminium. In the longer-term, as coal-based aluminium production in China is phased out, new Australian aluminium production based on firmed wind and solar may become competitive. But this will depend on how much new hydroelectricity can be produced in places such as Russia and Africa.

Box 4: It is cheaper to store hydrogen than electricity

CSIRO estimates that a hydrogen tank – the most expensive form of hydrogen storage – would cost about $1,100 per kilogram of storage capacity, if built in 2025.[a] This is equivalent to about $9,000 per gigajoule.

A separate CSIRO study estimates that long duration grid-scale battery storage will cost about $300 per kilowatt-hour of storage capacity by 2025.[b] This is equivalent to more than $80,000 per gigajoule.

Other factors affect this calculation, such as conversion efficiencies and the potential for future cost reductions. But the capital cost of hydrogen storage is lower by an order of magnitude, and so these other factors will not affect the overall conclusion.

a. CSIRO (2018, p. 84).
b. Graham et al (2020, p. 40). Long duration storage is for 8 hours; shorter duration storage is more expensive per kilowatt-hour.

2.4.2 Green steel is more affordable than green ammonia in the near-term

Australian-made green steel and green ammonia are likely to remain more expensive than conventional fossil fuel-based production processes for the foreseeable future. In the absence of a cost penalty on emissions, purchasers will need to pay a 'green premium' to purchase low-emissions steel or ammonia (Figure 2.2 on the next page). This is true even at green hydrogen prices as low as US$1 per kilogram, which is consistent with some long-term price forecasts.[57]

57. BNEF (2020, p. 5).

Hydrogen prices of US$3 per kilogram, which is at the low-range of today's cost of renewable hydrogen,[58] give a green premium of about 60 per cent for steel, and more than 100 per cent for ammonia.

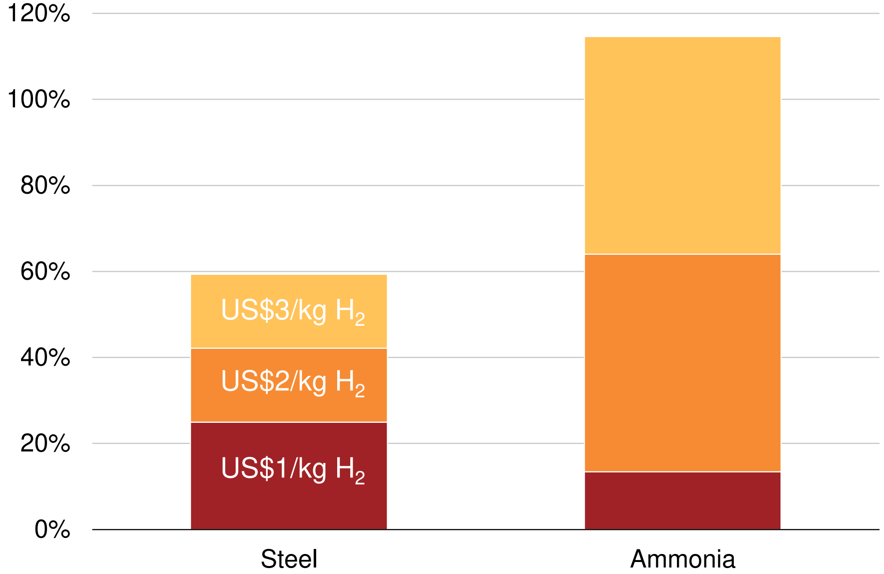
At low hydrogen prices, the economics of Australian-made green steel and green ammonia are good – they are only 25 per cent and 13 per cent more expensive than recent prices of fossil fuel-based production respectively. Importantly, the nearer-term economics of green steel look better than for ammonia. Using green steel made with hydrogen costing US$2 per kilogram would add only a tiny fraction to the cost of a steel-intensive end product. A typical car would be about 1 per cent more expensive.[59] Residential construction costs would increase by less than 1 per cent.[60] And costs for major rail and road tunnel infrastructure projects would rise by no more than 0.5 per cent.[61]

The cost of reducing emissions by using green steel and green ammonia are similar if hydrogen costs US$2 per kilogram, at about A$150 per tonne of carbon dioxide avoided. At US$1 per kilogram hydrogen, abatement from ammonia is cheaper – A$30 per tonne as opposed to A$90 for green steel. But at higher hydrogen costs, abatement from green ammonia is more expensive than from green steel.[62]

58. IEA (2019f).
59. Grattan analysis of ETC (2018a, p. 19) and World Steel Association (2020).
60. Grattan analysis of Deloitte Access Economics (2018, pp. 38–47, 74–77). This study provided estimates of the value of steel inputs in double-storey houses, townhouses, and low-rise apartments. Estimates for steel inputs into high-rise residential apartment buildings were derived from information on the Gold Coast's Q1 skyscraper, Australia's tallest residential building: Skypoint (2020).
61. Grattan analysis of major infrastructure projects including Sydney's WestConnex, Sydney Metro, Melbourne Metro, and Inland Rail: WestConnex (2017), Transport for NSW (2012, Chapter 17, pp. 10, 16), Transport for NSW (2016, p. 882), AJM Joint Venture (2016, pp. 47–49) and ARTC (2020).
62. These costs assume moving from integrated steel production to green steel, and moving from the world average emissions intensity of ammonia production (reflecting a mix of gas- and coal-based production) to green ammonia.

Figure 2.2: Green steel is more cost-competitive than green ammonia in the near-term

Green premium (additional cost of hydrogen-based product over cost of fossil fuel-based product) for Australian-made green steel and green ammonia



Notes: The green premium is calculated as the estimated cost of a low-emissions commodity, divided by the market price of the emissions-intensive equivalent, less 100 per cent. Market prices are for the period 2015 to 2019 inclusive. Steel prices are for export hot rolled coil. Ammonia prices are for the US Gulf market. Green steel and ammonia costs are based on production in eastern Australia, assuming either US$1, US$2, or US$3 per kilogram. US$3 per kilogram is at the low end of estimates of the cost of renewable hydrogen today: IEA (2019f). Green steel and ammonia costs are calculated based on various sources as detailed in Appendix A.2.

Sources: Grattan analysis, Steel Benchmarker (2019), and USGS (2020a, p. 116).

Green ammonia production does have an important short-term advantage over green steel. Renewable hydrogen can be easily blended with fossil-based hydrogen in existing ammonia plants, avoiding the need for expensive new capital equipment. This is also true of plants that use gas to make direct reduced iron, but these plants support less than 10 per cent of global steel production.[63]

2.4.3 Australia can produce green steel cheaper than many of its neighbours

Today Australia is a globally significant exporter of the two key inputs to steel-making – we produce 38 per cent of the world's iron ore[64] and 18 per cent of the world's metallurgical coal.[65] Yet we produce only 0.3 per cent of the world's steel.[66] This is because it is cheaper to ship these key inputs to major manufacturing and steel-consuming countries, such as China, Japan, Korea, and India. Shipping typically adds less than 10 per cent to the total cost of Australian coking coal delivered to major Asian markets.[67] The cost is too small to overcome the disadvantages of producing steel in Australia, such as high wages.

But using hydrogen rather than coking coal turns the economics of steel-making on its head. Shipping hydrogen is much more expensive than for coking coal. Shipping to Asian markets could easily double the cost of hydrogen relative to the cost of using it in Australia.[68]

63. World Steel Association (2019).
64. USGS (2020a, p. 89).
65. Grattan analysis of IEA (2019b) and Department of Industry, Science, Energy and Resources (2020, p. 46).
66. World Steel Association (2019).
67. Grattan analysis of coal shipping charter rates and Department of Industry, Science, Energy and Resources (2020).
68. Grattan analysis of CSIRO (2018) indicates hydrogen shipping costs in the order of US$1.50 per kg. Some studies – such as BNEF (2020) – forecast hydrogen costs of less than US$1 per kg.

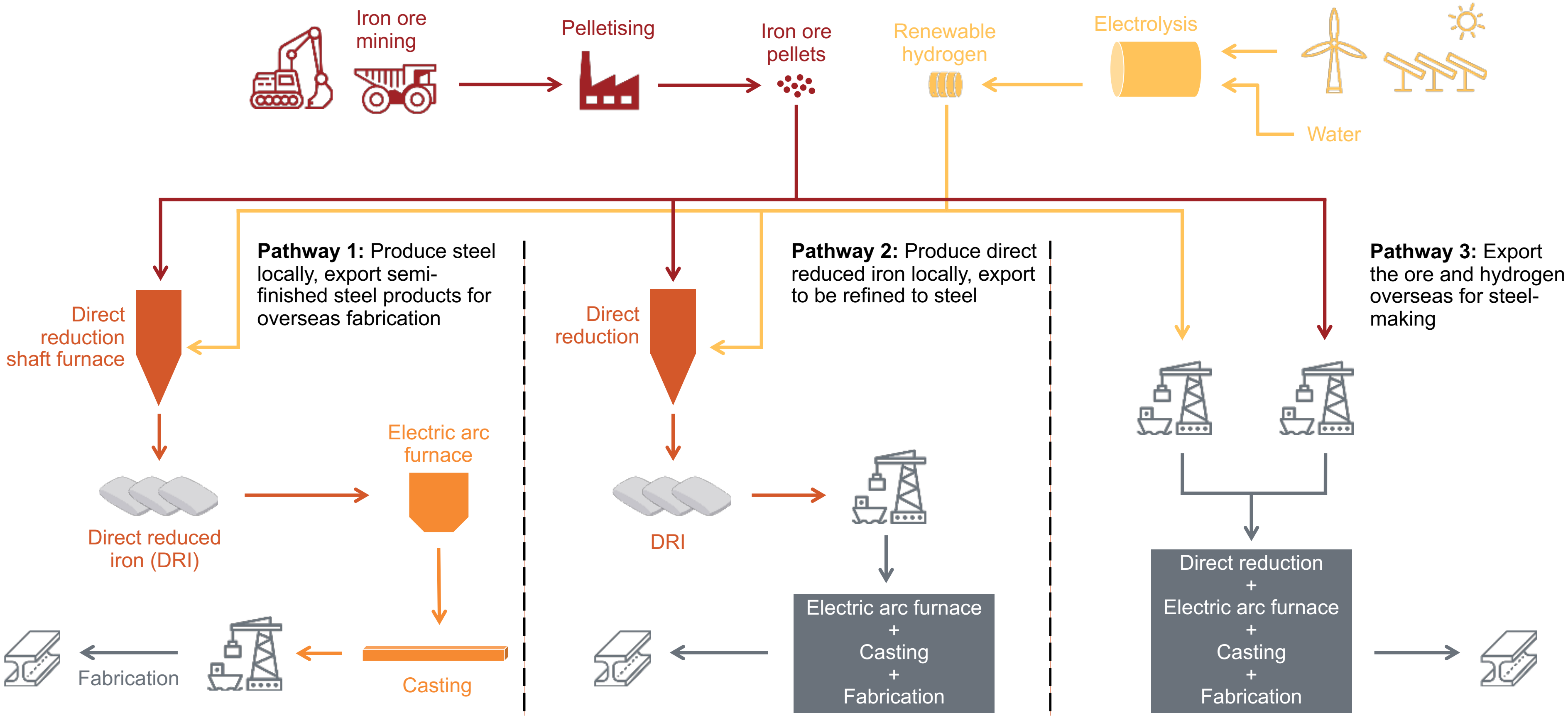
The cost of shipping hydrogen strongly favours making green steel – or at least the hydrogen-intensive direct reduction process – where the hydrogen is made. This is likely to be in renewable-rich Australia, rather than in countries that have lower-quality renewable energy resources and limited land, such as Japan, Korea, Indonesia, Vietnam, and Thailand.[69]

Australia's renewable resources could underpin the supply of steel to our Asian trading partners in three main ways (Figure 2.3 on the following page). The first involves the direct reduction of iron ore to iron metal (sometimes called 'direct reduced iron'), and the further refining and casting of that iron into a semi-finished steel product for export, all occurring in Australia. The second involves Australia producing direct reduced iron for export, and the importing country refining the direct reduced iron into steel. The third involves Australian hydrogen[70] being shipped to the country needing the steel, which would then use the hydrogen to make steel.

The economics of these three pathways vary depending on the country needing the steel (Table 2.2 on page 24). For relatively high-wage countries such as Japan or Korea, it makes sense for Australia to export steel. But for lower-wage countries such as Indonesia, the cost of steel made in Indonesia with Australian direct reduced iron is essentially the same as the cost of Australian-made green steel. In neither case does it make sense for Australia to export hydrogen to make direct reduced iron in the steel-consuming country. And hydrogen prices estimated by Bloomberg New Energy Finance[71] indicate that

69. In future, China and India may seek to import energy-intensive commodities due to land and renewable energy resource constraints. But for the purpose of this report, we assume that Australia will primarily export green steel to north-east and south-east Asia.
70. This could be in the form of liquefied hydrogen, or another hydrogen carrier such as ammonia.
71. Ibid.

Figure 2.3: Green steel export pathways



Notes: All three pathways require low-emissions electricity in each step. Iron ore mining and pelletising need not occur in Australia.

Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

green steel made in Japan with local hydrogen will be more expensive than green steel made in Australia.

These results reflect the economic advantages of different countries. Australia's lower-cost hydrogen, plus the high cost of hydrogen transport, give it a clear advantage in undertaking direct reduction. But turning direct reduced iron into steel requires more labour and less energy than the direct reduction process, giving low-wage countries an advantage in that step of the process. Overall, the economics of these pathways are very similar for low-wage countries, and a mix of approaches is likely – Australia could export some steel directly, and some direct reduced iron. It is also possible that Australian direct reduced iron could be turned into steel in a low-wage country, and on-sold to a third country. This potential mix of approaches is reflected in the analysis in Chapter 3.

2.5 Technical and economic challenges remain

2.5.1 Hydrogen direct reduction is not commercially proven

Hydrogen-based direct reduction is not made commercially at present, but the technology is based on commercially-proven gas-based direct reduction. The two major technology providers of gas-based direct reduction claim that their existing plant could run on pure hydrogen with little or no modification, though this has not happened in practice.[72]

Hydrogen direct reduction pilot plants – one using each of the two main gas direct reduction technologies – are being built or planned in Sweden and Germany.[73] Technical challenges will arise in moving from gas to hydrogen direct reduction, and these pilots will help to identify and address these challenges.

72. Midrex (2020); and Energiron (2020a).
73. SSAB (2019); ArcelorMittal (2019); and Tenova HYL (2018).

Table 2.2: Australia could export steel directly, or export direct reduced iron for further processing in low-wage countries
Cost of semi-finished steel landed in the steel-consuming country, A$ per tonne

Steel-consuming country	Japan	Japan	Japan	Indonesia
Hydrogen price scenario	Grattan	BNEF 2030	BNEF 2050	Grattan
Pathway 1: Australia exports steel	937	874	797	929
Pathway 2: Australia exports DRI	968	905	828	930
Pathway 3: Australia exports hydrogen	1,099	–	–	1,026
Steel-consuming country makes steel with local hydrogen	–	1,010	876	–

Notes: Lowest-cost pathways for each hydrogen price scenario and consuming country are shown in grey. In the Grattan hydrogen price scenario, hydrogen costs are assumed to be US$2/kg hydrogen in Australia, and US$2/kg plus transport costs for Japan and Indonesia. Transport costs based on Grattan analysis of CSIRO (2018). BNEF is Bloomberg New Energy Finance: BNEF (2020). BNEF have 2030 hydrogen cost estimates of US$1.48/kg and US$2.85/kg for renewable hydrogen produced in Australia and Japan respectively, and 2050 costs of US$0.84/kg and US$1.74/kg respectively. Steel cost analysis is based on various sources as outlined in Appendix A.2.

Sources: Grattan analysis based on the sources cited above.

The time required to address these challenges is uncertain, but is unlikely to delay a broader move to commercial-scale production given that time is also needed to improve the economics of hydrogen production. For example, Swedish steel maker SSAB is targeting 2026 for commercial-scale green steel production.[74]

Australia will face some specific challenges in making the transition to green steel. The chemical composition of many Pilbara iron ores makes them difficult to concentrate into pellets suitable for direct reduction.[75] Some Australian iron ore miners will need to overcome these challenges to retain market share if the world moves decisively towards direct reduction. But iron ore and pellets are globally traded products, and these challenges do not damage the prospects of making green steel in Australia – more suitable ores are also available if needed, both in Australia and in other countries.

2.5.2 Australia will face stiff competition

Even though it makes sense for an energy-rich country such as Australia to export direct reduced iron or green steel to its energy-poor neighbours, Australia will not have it all its own way in these markets. Australia will face stiff competition both from other renewable-rich locations that can produce cost-competitive renewable hydrogen – such as the US, Argentina, northern Africa, the Middle East, and China (see Figure 2.1 above) – and locations that can produce affordable low-emissions fossil hydrogen using natural gas and carbon storage – such as the US, Russia, and the Middle East.[76] These locations will be competitive in green ammonia as well as green steel.

Low-emissions steel can also be produced using carbon capture and storage (CCS), without first producing hydrogen. Gas-based direct reduction produces a relatively pure stream of carbon dioxide that can be readily captured and stored. This is already happening on a commercial basis in the United Arab Emirates.[77] This approach will be particularly attractive in places with low-cost gas and high-quality carbon dioxide storage reservoirs, such as the US, Russia, and the Middle East. Large-scale adoption of this technology could happen as part of a broader move to decarbonise the steel industry, although this could also stretch the availability of low-cost carbon dioxide storage reservoirs, pushing up costs.

Integrated steel-making can also use CCS, but the multiple sources of carbon dioxide within this process[78] and their relatively low concentration makes this technologically and economically difficult. Carbon capture rates of about 50 per cent are likely to be feasible, but it is economically and technically challenging to achieve capture rates of 80 per cent or higher.[79]

The uncertain interplay of competing technologies and production locations means that Australia should be proactive, but flexible, in positioning itself in these emerging markets. Chapter 4 outlines policies that governments at all levels can take to ensure Australia is well-placed to capture these opportunities.

74. SSAB (2019).
75. Australia (2015).
76. IEA (2019f).
77. Emirates Steel (2020) and Global CCS Institute (2019). The carbon dioxide is being used to increase oil production from declining fields, so called ‘enhanced oil recovery’.
78. ‘Integrated’ steel-making is so called because it integrates a number of distinct processes. Each of these produces emissions. The processes include: a sinter plant (which agglomerates iron ore fines into larger pieces suitable for the blast furnace), a coke oven (reducing coking coal to coke), the blast furnace, the basic oxygen furnace and, often, a power plant that burns exhaust gases from these other processes. See Appendix A.1 for more detail.
79. Fischedick et al (2014).

3 Carbon workers can help capture this opportunity

New clean energy industries can plausibly create new jobs at a scale comparable to existing carbon-intensive industries (Table 3.1). The scenarios considered in this chapter translate to between 40,000 and 55,000 ongoing jobs across green steel, green ammonia, and biofuels for aviation – very similar to today's 55,000 geographically-concentrated carbon workers.

And the regions that host carbon-intensive industries today are well placed to host these new jobs. Carbon workers, and the port and electricity infrastructure that supports them, can help Australia capture opportunities in emerging clean energy industries. If existing carbon jobs come under threat, these workers will become available to work in new industries, in large enough numbers to do this at world-scale. This offers hope for a smooth transition for these workers and the regions they live in.

Carbon workers are particularly important to build a world-scale green steel industry, which would require tens of thousands of workers. Labour and construction costs are far lower in eastern Australia than in the Pilbara, so it would be cheaper to take the iron ore to the large pool of workers in central Queensland or the Hunter Valley than to try to attract workers from the south or east to the Pilbara.

Other regions with carbon workers have their own opportunities. The Pilbara or Bunbury (near Collie) could provide a small-scale, but crucial, stepping stone to a global-scale green steel industry using gas-based direct reduction. Port Kembla and Whyalla have good prospects for moving from existing fossil fuel-based steel-making to supply low-emissions steel to the domestic market. Portland, Collie, and the Latrobe Valley could produce sustainable biofuels. And any of these locations could feasibly produce low-emissions hydrogen or ammonia for export.

Table 3.1: Clean energy manufacturing could credibly deliver a similar number of jobs to existing regionally-concentrated carbon industries

Carbon-intensive industry	Regionally-concentrated workers	Potential clean energy industry	Plausible jobs
Coal mining	35,000	Steel	25,000
Fossil fuel electricity	4,000	Biofuels for aviation	10,000
Rail freight transport	3,500	Ammonia	5,000 – 20,000
Oil and gas extraction	3,000		
Aluminium smelting	2,500		
Iron and steel smelting	2,000		
Port operations	1,500		
Other	4,000		
Total	55,000	Total	40,000 – 55,000

Notes: 'Concentrated workers' live in regions with significant proportions of the workforce employed in carbon-intensive industries, as outlined in Figure 1.4 on page 10. In regions with significant coal mining activity, all rail freight and port jobs have been deemed carbon jobs, but some will be associated with non-coal freight. Potential clean energy jobs are for manufacturing plant and, for steel and ammonia, electrolyser jobs for hydrogen supply – they exclude construction jobs and ongoing renewable energy jobs. Steel jobs are based on the scenario set out in Table 3.2 on page 30. Biofuel jobs estimates are based on full utilisation of available biomass set out in Crawford et al (2016). The lower estimate for ammonia is for utilisation as a chemical only; the upper estimate is based on a scenario where the global shipping industry adopts ammonia as a fuel (see Section 3.8).

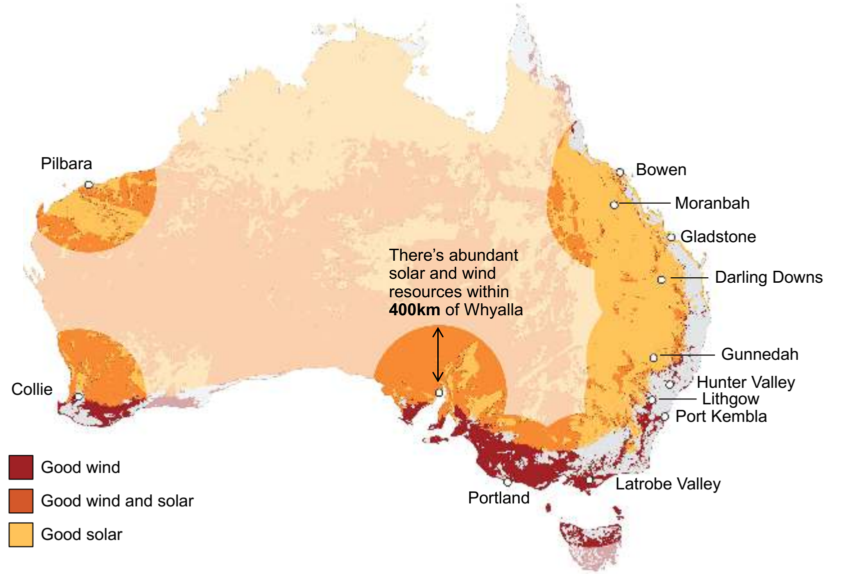
Sources: Grattan analysis of ABS (2017) and assumptions in Appendix A.2.

3.1 Carbon-intensive regions have the resources and infrastructure to host low-emissions industries

Regions that currently host carbon-intensive industries are particularly well suited to hosting new low-emissions industries built on clean energy. Almost all of these regions are within an accessible distance to good-quality wind and solar resources (Figure 3.1). In addition, the Latrobe Valley has abundant brown coal and access to high-quality carbon storage reservoirs, which may be able to support cost-competitive low-emissions hydrogen production.

The port and electricity transmission infrastructure that supports existing carbon-intensive activities could also support new, low-emissions activities. Carbon-intensive regions such as central Queensland, the Hunter, the Pilbara, Whyalla, Portland, and the Pilbara have good port access. And all carbon-intensive regions have access to high-voltage electricity network connections – these are particularly strong in the Hunter and Latrobe valleys, near Lithgow, and at Portland. This is important both for importing electricity from the grid and for exporting power when variable renewable supply is excess to requirements.

Figure 3.1: Carbon regions are close to high-quality renewable resources
Wind and solar resources within 400km of carbon-intensive regions



Notes: High-quality resources are defined to be areas with average wind power-density of at least 450 W/m² and average daily solar photovoltaic potential of at least 4.5 kWh/kWp. Offshore wind potential is not shown.

Sources: Grattan analysis of Global Wind Atlas (2020) and Global Solar Atlas (2020).

3.2 Carbon workers and their communities are crucial to capturing clean energy opportunities

'Hard' infrastructure – such as ports and grid connections – is not enough to capture clean energy opportunities. Skilled people and supportive communities are crucial. Carbon-intensive industries have built a skilled workforce concentrated near key infrastructure. This workforce can expand into new areas or, in the event that carbon-intensive industries come under pressure, be progressively redeployed. In this way, clean energy jobs offer workers and regions a good (though not certain) hedge against significant shifts away from carbon-intensive industries. If the world decarbonises rapidly, opportunities in clean energy industries should also emerge quickly;

if the world is slow to decarbonise, existing industries and jobs will continue for longer.

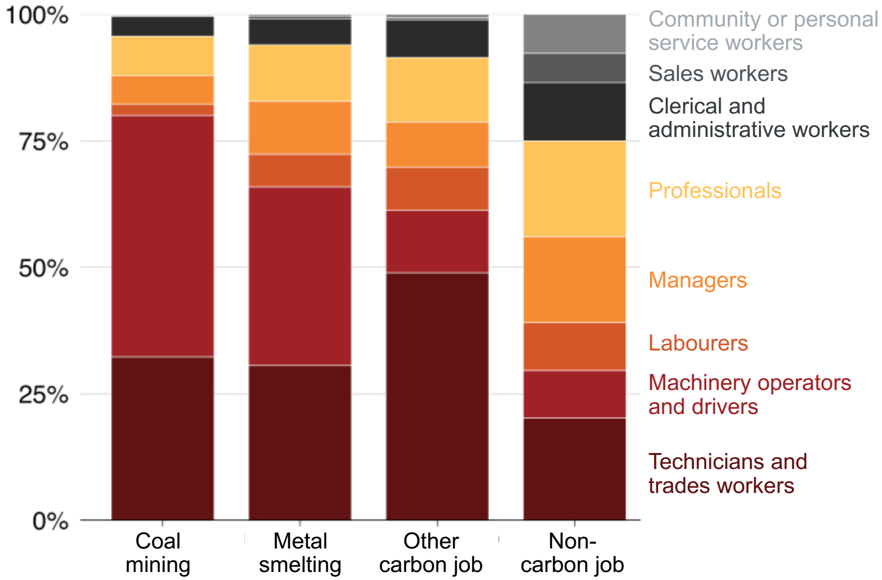
Importantly, the skills required in green steel are likely to be similar to those currently used in carbon-intensive metal smelting, and these skills overlap broadly with those of coal workers. Figure 3.2 shows that metal smelting and coal mining both require large numbers of technicians, trades workers, and machinery operators – in carbon regions, about 80 per cent of coal mining jobs or 66 per cent of metals smelting jobs need these skills.[80] By contrast, these skills are used in less than 30 per cent of jobs in other parts of the local economy. No doubt some retraining will be required to redeploy coal workers in an emerging green steel industry, but the prospects for this are much better than in health, education, or tourism, for example.

New clean energy manufacturing jobs are also likely to pay better than other jobs in the same regions. These jobs are likely to have similar pay to existing jobs in metals manufacturing: in 2016, full-time workers in steel and aluminium smelting typically earned about $1,750 per week.[81] These jobs did not pay quite as well as coal mining jobs – those workers typically earned more than $2,000 per week. But they paid better than most other jobs: median full-time incomes in these communities were less than $1,200 in 2016.[82]

The importance of large, competitive labour markets is illustrated by comparing the cost of producing green steel in the populous eastern states with doing so close to the iron ore resource. The Pilbara is the world's largest iron ore province, but it is likely to be more expensive to make steel there than in east coast locations such

Figure 3.2: Jobs in metal smelting require similar skills to jobs in coal mining

Share of workers



Notes: Includes only full-time workers who live in regionally-concentrated carbon communities (see Figure 1.4). Metal smelting includes only iron, steel, and aluminium. Excludes workers who did not state or inadequately described their occupation.

Source: Grattan analysis of ABS (2017).

80. These regions are shown in Figure 1.4 on page 10.
81. Values are in 2016 dollars, derived from responses to the Census: Grattan analysis of ABS (2017). Includes only workers in carbon regions as shown in Figure 1.4 on page 10.
82. Ibid.

as central Queensland or the Hunter Valley (Figure 3.3). Labour costs are significantly higher in the Pilbara than in other parts of Australia, and this causes higher construction and ongoing operations and maintenance costs. Higher building materials costs and the need to cyclone-proof infrastructure exacerbate the Pilbara's cost disadvantage.[83]

3.3 Green steel could provide tens of thousands of jobs in central Queensland and the Hunter Valley

A range of clean energy industries could plausibly provide hundreds, or even thousands, of new jobs in Australia. But very few can plausibly provide tens of thousands of jobs, comparable to the number in the key coal mining regions of central Queensland and the Hunter Valley.

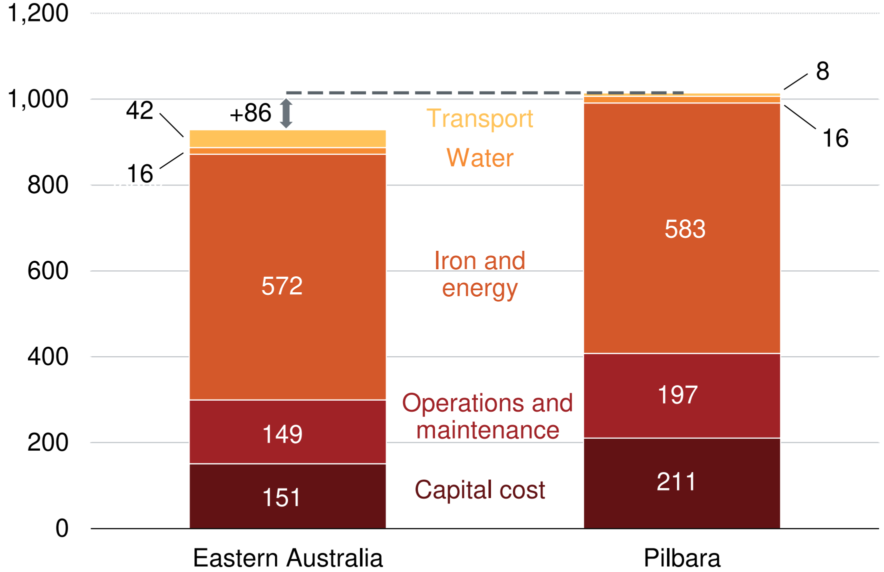
Green steel is the exception. It could create the tens of thousands of jobs needed to give hope for a smooth transition for the large numbers of coal workers that live in those regions. In doing so, an Australian green steel industry could help to resolve Australia's climate conundrum – the tension between the interests of carbon-intensive regions and the broader national interest on climate action (see Chapter 1).

Table 3.2 on the next page presents an illustrative green steel industry in central Queensland and the Hunter Valley. We have not modelled

83. Grattan analysis of Songhurst (2018) indicates that LNG liquefaction plants completed in north-west Australia between 2014 and 2018 were about 40 per cent more expensive than those completed in Queensland over the same period, after taking account of differences in the type of gas processed. A key national construction cost guide estimates that construction of a range of building types is about 50 per cent more expensive in the Pilbara than in coastal industrial regions in NSW and Queensland: Grattan analysis of Rawlinsons (2019, pp. 40–50, 911). Research done for the Pilbara Development Commission estimated an initial cost premium of 40 per cent, but anticipated that this would reduce to zero over multiple phases of a large renewable energy project: Mella et al (2017, p. 63).

Figure 3.3: It is cheaper to move iron ore to existing workers than move workers to the iron ore

Cost of semi-finished steel landed in Indonesia, A$ per tonne



Notes: Cost estimates assume a hydrogen cost of US$2 per kilogram. Steel production involves direct reduction using hydrogen, smelting in an electric arc furnace, and continuous casting to a semi-finished tradable product (slab or billet). Labour costs are assumed to be 70 per cent higher in the Pilbara than in eastern Australia, based on regional differences in manufacturing wages: ABS (2017). Construction costs are assumed to be 40 per cent higher in the Pilbara than eastern Australia, based on a comparison of construction costs of liquefied natural gas projects: Songhurst (2018). Transport costs are estimated based on ship charter and fuel costs, and include a premium to reflect the future use of zero-emissions ammonia in shipping. Shipping routes are to and from Dampier (the Pilbara), Newcastle (eastern Australia), and Jakarta (Indonesia). Steel is assumed to be 'back-hauled', that is, transported back on otherwise empty iron ore ships to Dampier at minimal additional cost, but with an additional handling cost of US$3 per tonne, before further shipping to Jakarta.

Sources: Grattan analysis based on assumptions detailed in the Notes and in Appendix A.2.

a scenario that exactly replaces the 23,200 jobs for carbon workers in central Queensland, or the 16,200 in the Hunter. But comparable scale – we have modelled a scenario involving 15,000 jobs in central Queensland and 10,000 in the Hunter – is achievable. These job estimates are conservative, because they ignore construction jobs. Significant numbers of construction jobs would be created to build the required steel plant, the electrolysers, and the renewable generators to power them. The 25,000 modelled jobs in what are presently carbon-intensive regions do not include renewable ongoing jobs, which are likely to be geographically dispersed and therefore in a range of different locations. We have also excluded the jobs associated with transporting iron ore and steel.

This scenario has been calibrated to reflect the economics of green steel production in Australia. Half of the direct reduced iron produced in Australia is assumed to be exported for further processing in low-wage countries,[84] and half to be exported as steel directly to the consuming country. This assumption reflects that the cost of these two pathways is very similar, and a mix of approaches is likely (Section 2.4.3 on page 22).

This scenario relies on Australia producing almost 7 per cent of the world's steel, a significant increase on the 0.3 per cent it produces today.[85] But this market share is not unrealistic. Australia's rich bauxite and fossil fuel resources enable it to manufacture about 15 per cent of the world's alumina today.[86] And Australia's share of world bauxite production (27 per cent) is comparable to, but lower than, its share of iron ore production (38 per cent).

Significant investment – almost $200 billion in today's dollars – would be required for Australia to produce almost 7 per cent of the world's

84. We have modelled costs for Indonesia, but exporting to other countries, such as Thailand, Vietnam, China, or India is possible.
85. World Steel Association (2019).
86. USGS (2020a, p. 31).

Table 3.2: Green steel could deliver tens of thousands of jobs

	Central Queensland	Hunter Valley	Combined
Ongoing plant jobs in region	15,000	10,000	25,000
Direct reduced iron (DRI) output (Mt per year)	60	35	95
DRI exported (Mt per year)	30	17.5	47.5
Steel exported (Mt per year)	25	15	40
Output as share of 2050 global steel market (including steel produced from exported DRI)	4%	2.5%	6.5%
Output as share of today's integrated steel production by prospective trading partners	30%	20%	50%
Annual value ($b)	40	25	65
Capital investment ($b)	115	80	195
Renewable generation capacity required (GW)	75	60	135
Renewable ongoing jobs (mostly outside region)	2,000	1,500	3,500
Water input (GL per year)	200	150	350
Land required (share of state area)	0.45%	0.65%	0.5%

Notes: Assumes half of Australia's DRI production is exported, and half is used to produce steel in Australia. All jobs are ongoing full-time equivalent jobs, and exclude construction jobs. Plant jobs include operation and maintenance of both steel plant and electrolysers for hydrogen supply. Prospective trading partners are Japan, Korea, Indonesia, Malaysia, Taiwan, and Vietnam.

Source: Grattan analysis based on assumptions in Appendix A.2.

steel. This amount of investment is large, but is much less than the $350 billion invested in Australia by the oil and gas industry in the past decade alone.[87] In the same way, building a green steel industry would require significant investment by international steel companies.

The economic prize is substantial. The annual output of a green steel industry of this scale would be about $65 billion in today's dollars. This is only slightly smaller than the value of Australia's export coal industry today.[88]

A green steel industry of this size would require substantial, but deliverable, amounts of electricity and water. It is likely that much of the required 135 gigawatts of renewable generation would be located west of the Great Dividing Range in less-populated, and sunnier, locations. Generation of this scale would probably require about 0.5 per cent of the area of Queensland and NSW – and much of this land could continue to be used for grazing or other purposes. The amount of water needed – about 350 gigalitres – is equivalent to three or four large desalination plants.[89] But even using this relatively expensive source of water, water supply would be only 2 per cent of the total cost of green steel (Figure 3.3 on page 29).

3.4 The Pilbara could export green direct reduced iron

The economics of making green steel in the Pilbara do not look attractive (Figure 3.3 on page 29) – the cost of labour is just too high. Even if the Pilbara's additional construction and labour costs relative to the east coast were halved, green steel produced in the Pilbara would still be more expensive than that produced on the east coast.

But the economics of producing green direct reduced iron are slightly different, because it is much less labour-intensive (Section 2.4.3). If the Pilbara does manage to halve its construction and labour cost disadvantage relative to the east cost of Australia, it could become a cost-effective location for exporting direct reduced iron for further processing.

3.5 Western Australia could provide an important stepping stone to green steel

Hydrogen-based direct reduction is not yet technologically proven at commercial scale, and it is likely to be some time before the economics of hydrogen production improve. But gas-based direct reduction could offer a stepping stone to green steel – it is commercially proven already, and gas is cheaper than hydrogen. It produces only about half the emissions of steel made in an integrated steel mill.[90] And emissions can be reduced further by blending increasing amounts of renewable hydrogen into the plant, meaning that emissions are not 'locked in' for the life of the plant.

Western Australia's low-cost gas makes it an attractive location for gas-based direct reduction. In fact, Bunbury (near Collie in south-western WA) – which has both affordable labour and cheap gas – looks to be the cheapest place in Australia to produce direct reduced iron to feed electric arc furnaces located in eastern Australia (Table 3.3 on the next page).[91] If the Pilbara was able to reduce its traditionally

87. APPEA (2019).
88. In 2018-19, Australia exported coal worth almost $70 billion: Department of Industry, Science, Energy and Resources (2020).
89. Major urban desalination plants in Australia range in size from 45 to 150 GL per year: Australian Water Association (2020).
90. A modern integrated steel mill produces about 2.1 tonnes of CO_2 per tonne of steel: IEA Environmental Projects (2013). The direct emissions from a gas-based direct reduction plant are about 0.6 tonnes of CO_2 per tonne of steel, based on gas consumption in Energiron (2020b). Additional emissions from electricity inputs are likely to be less than 0.5 tonnes of CO_2 per tonne of steel, but depend on the electricity source.
91. Even if direct reduced iron is produced in Western Australia, it is likely that steel will continue to be produced in eastern Australia given the existing casting and

high labour and construction costs, it may also prove lower-cost than eastern Australia.

A typical commercial scale gas-based direct reduction plant in the Pilbara or Bunbury would create about 150 jobs.[92]

3.6 Port Kembla and Whyalla are likely to keep producing steel for Australia

Australia's steel primarily comes from integrated steel mills at Port Kembla (2.6 million tonnes per annum capacity) and Whyalla (1.2 million tonnes capacity). Scrap steel is recycled at smaller electric arc furnaces in Sydney (Rooty Hill), Melbourne (Laverton), and Newcastle (Waratah). And some steel is imported, primarily in the form of specialty steel products.

The steelworks at Port Kembla and Whyalla do much more than make crude steel. The steel made there is cast and further fabricated into many steel products, with shapes and characteristics to suit specific applications. The casting, rolling, coating, and other fabricating machinery is of high value, and is likely to remain in use to serve domestic needs.

These existing assets and the associated workers, as well as good access to renewable energy resources – particularly at Whyalla – give these sites good prospects for transitioning from traditional emissions-intensive steel-making to low-emissions alternatives.

Steel-making using direct reduction and electric arc furnaces require slightly fewer jobs per unit of output than integrated steel mills. So

fabricating plant located at Port Kembla and Whyalla, and the need to serve the eastern Australian market.

92. A typical commercial scale plant can produce about 2 million tonnes per year. Plants of this size typically have about 150 direct employees – see Table A.2 on page 44.

Table 3.3: Gas-based direct reduction is cheaper in Western Australian than on the east coast

Locations		Assumptions			Cost of cast steel ($/t)
Gas-based direct reduction	**Electric arc furnace, casting**	**Gas price ($/GJ)**	**Wages**	**Construction costs**	
Bunbury	Eastern Australia	5	Benchmark	Benchmark	736
Pilbara	Eastern Australia	4	Benchmark +35%	Benchmark +20%	743
Eastern Australia	Eastern Australia	8	Benchmark	Benchmark	756
Pilbara	Eastern Australia	4	Benchmark +70%	Benchmark +40%	772

Note: The wage and construction cost assumptions above are for the direct reduction process only, and are benchmarked to prices on the east coast of Australia. In all cases the electric arc furnace and casting processes are undertaken in eastern Australia, and so the wage and construction cost assumptions for that process stage are identical in each case.

Sources: Grattan analysis based on assumptions in Appendix A.2, ACCC (2018, p. 22), AEMO (2019, p. 62) and DBP (2020).

Port Kembla and Whyalla would have fewer jobs if these facilities transitioned to cleaner technologies. But doing so would enable them to continue primary steel-making and sustain existing fabrication jobs. If these regions hosted direct reduction and electric arc plant of similar capacity to their existing furnaces, about 80 per cent of the existing iron and steel jobs (including fabrication) would be retained. And about 70 per cent of jobs would be retained if direct reduced iron was shipped to these locations and processed in new electric arc furnaces.

3.7 Biofuels provide opportunities in other regions

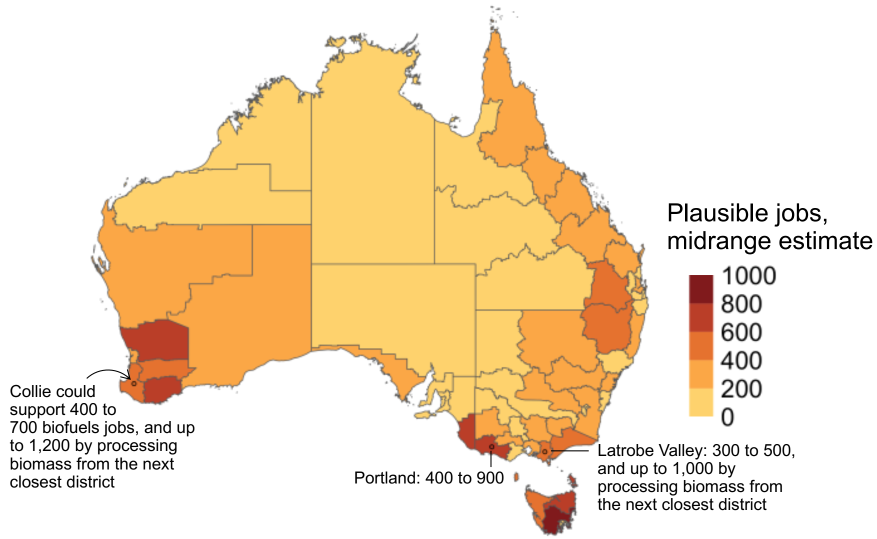
Several of Australia's carbon-intensive regions are also rich in biomass resources that could be used to make sustainable biofuels, such as for aviation. Potential sources of biomass include wastes from existing agricultural and forestry industries, municipal solid waste, and dedicated plantings of short-rotation tree crops such as mallee or acacia.[93]

By 2050 the biomass available from these sources could support a biofuel industry with about 10,000 jobs distributed nation-wide (Figure 3.4). Of Australia's carbon-intensive regions, Collie and Portland have particularly good biomass resources, potentially sufficient to support about 500 jobs in each region. The Latrobe Valley, the central Queensland sugar cane regions, and inland NSW also have significant biomass resources.

Australia's biomass resources are unlikely to be large enough to support large-scale biofuel exports, but they can provide a significant share of our own needs. Australia is likely to have enough waste biomass to supply all of its domestic aviation fuel requirements in 2050.[94] Additional biomass resources, such as dedicated plantings of short-rotation tree crops, would be needed to supply biofuels to other markets, such as international aviation or shipping fuels, or to make bio-plastics.

93. Sustainable biofuels (sometimes called 'second generation' biofuels) are made from non-food crops or wastes, and are produced in a way that does not compete with food production.
94. Biomass estimates are based on CSIRO analysis, excluding crop stubble and native grasses: Crawford et al (2016). Aviation fuel requirements in 2050 are estimated based on the 2020-to-2030 growth rate in domestic aviation emissions assumed in Department of Industry, Science, Energy and Resources (2019). Under international emissions accounting rules, Australia's emissions projections exclude flights entering or leaving Australia.

Figure 3.4: Many carbon-intensive regions have good biomass resources



Notes: Biomass estimates are based on CSIRO analysis: Crawford et al (2016). Grattan has adjusted the available amount of biomass to ensure the estimates are conservative: native grass and crop stubble are excluded because these resources vary each season and year. Estimates of available bagasse and waste biomass are halved to reflect that some of this resource is currently used for energy or other purposes. Crawford et al (ibid) assume 10 per cent of cleared farmland is used for short rotation tree crops. Available biomass estimates are then used to estimate potential biofuels jobs assuming 1,000 full-time jobs per million tonnes of biofuel production capacity – derived from Grattan analysis of 15 commercial-scale biorefineries (detailed in Appendix A.3). The range of estimates reflects the range of observed biomass-input-to-fuel-output ratios (broadly between 3 and 5 tonnes of input biomass per tonne of biofuel). These estimates are inherently uncertain due to the small number of commercial biorefineries in operation today, and the variety of feedstocks and refining processes used.

Sources: Crawford et al (ibid), and various sources as summarised in Appendix A.3.

3.8 Green ammonia could also provide thousands of jobs

Australia could capture opportunities in green ammonia, but they are likely to be smaller than in green steel – particularly in terms of jobs. If Australia was to produce 6.5 per cent of the world's ammonia using electrolysed hydrogen by 2050 – that is, the same share as assumed for steel – this would create up to 5,000 ongoing jobs.[95] These jobs could be located anywhere in Australia that has cost-competitive renewable energy to make green hydrogen, good port access, and sufficient land and labour.

The potential for green ammonia exports could be much greater if the global shipping industry adopted ammonia as a fuel. This is plausible in the long term, but in the interim shipping may use biofuels – particularly because biofuels can be used in existing engines without modification.[96] If global shipping moved exclusively to ammonia and Australia won a 6.5 per cent market share, this could create about another additional 15,000 ongoing jobs.[97]

95. Production of ammonia for chemical use only (that is, ignoring the production of ammonia as a hydrogen carrier). Estimate based on the job intensity of a benchmark ammonia plant – see Appendix A.2.
96. ETC (2018d, p. 21).
97. Estimate based on the energy density of ammonia, the size of shipping fuel market calculated in Table 2.1 on page 18, and the job intensity of ammonia production as detailed in Appendix A.2.

4 Governments should act now

Australia's clean energy opportunities are large, but they are far from certain. Governments cannot single-handedly drive the creation of new global-scale industries, nor invest the hundreds of billions of dollars required. But they should implement policies that plan for, and can facilitate, this future.

A two-phase approach is needed. First, a preparation phase over the next decade, in which Australian governments take targeted policy action to give us our best chance of capturing opportunities that may emerge later on. Second, an expansion phase, which is both less certain and less dependent on Australian policy, because it will be driven by global markets and policies, and by private investment.

The federal government should help Australian steel-making move to lower-emissions technologies over the next decade. Government funding for a steel 'flagship' project would underpin investment in lower-emissions technologies and build the skills and capabilities Australia will need to create an export-scale green steel industry in the expansion phase.

Governments should continue their efforts to build capability in making and storing hydrogen, consistent with the National Hydrogen Strategy. In particular, governments should fund pre-commercial geotechnical studies to better understand the potential for hydrogen storage in salt caverns. And governments can help workers capture new opportunities by supporting their skills development and retraining.

Policy can also help create a new biofuel industry. The federal government should examine the costs and benefits of requiring that a share of domestic aviation fuel be supplied from sustainably produced biofuels. This would reduce emissions, build local technical capability, and create new regional industries – benefits that may well justify the cost of such a scheme to air travellers.

4.1 Australia should position itself to capture emerging opportunities

There is no guarantee that Australia will ultimately capture almost 7 per cent of a decarbonised global steel industry, or that it will create 25,000 new jobs in the coal regions of Queensland and NSW. The supply of and demand for green commodities, and the pace of global decarbonisation, are inherently uncertain.

But uncertainty is not an excuse for inaction. Even allowing for uncertainty, Grattan's scenario analysis indicates that the potential opportunities are sufficiently large to justify targeted measures today. These measures should position Australia to build the capabilities needed to capture emerging opportunities, if the key economic and policy factors move in our favour. Targeted actions today could have big rewards tomorrow.

Actions beyond those canvassed in this report may be required in future. These can be calibrated in due course, using the latest information. We will know a lot more about the prospects of both green and carbon-intensive industries in 2025 than we do today, and a lot more again in 2030. This adaptive approach is consistent with that advocated by the COAG Energy Council for hydrogen exports in its National Hydrogen Strategy.[98]

4.2 The federal government should build capability in making low-emissions products

A market for green commodities is emerging, particularly among car manufacturers concerned about their supply chain emissions.[99] But this

98. COAG Energy Council (2019, p. 27).
99. Lord (2019, pp. 11, 24).

market is new and demand is uncertain. Low-emissions commodities are generally more expensive than their emissions-intensive equivalent. It would be risky to build a commercial-scale low-emissions plant just to satisfy the green premium market.

Australia should use the next decade to create a foothold in the emerging green steel market. The best way to do this is through direct government funding to support private investment in higher-cost, but lower-emissions, steel production – a steel 'flagship' project (Box 5). This would help build the skills and capability needed in a future export-oriented expansion phase.

Conditions in Australia's steel market mean that direct government funding is likely to be superior to other, more complicated, policy approaches. One alternative is a low-emissions steel procurement mandate, similar to the Renewable Energy Target that requires electricity retailers to buy a growing share of their power from renewable sources. That approach has worked well, but the electricity market has many buyers and sellers. By contrast, the Australian steel market is dominated by just two main producers, and a market-based procurement mandate could result in one of those producers dominating the low-emissions steel market. This is compounded by the large scale needed for economic steel production – the 'lumpy' nature of investment would make it unlikely that both incumbent producers could justify separate investments in low-emissions steel. The ease with which steel can be imported and exported adds to the complexity of using this approach for steel.

The government funding required to support a low-emissions steel project is not small. Government funding in the order of $500 million is likely to be necessary to underpin a multi-billion dollar modernisation of Australia's steel industry.[100] Though the investment is large, it would also support significant emissions reductions compared to Australia's

100. Grattan analysis based on assumptions in Appendix A.2.

Box 5: A steel flagship project

A steel flagship project would involve incumbent and potential new steel suppliers seeking government funding to invest in low-emissions steel technologies not currently used in Australia.

It should not be limited to green steel using hydrogen-based direct reduction, because this approach is too expensive today, and not yet proven at commercial scale. It should include low-emissions technologies such as gas-based direct reduction, which uses similar technology to hydrogen-based direct reduction and so would build directly relevant skills and knowledge. Blending increasing amounts of renewable hydrogen allows emissions to be reduced over time, and further builds skills relevant to making green steel.

Government funding can help draw out innovative proposals. This could include trial blending of gas with renewable hydrogen, to build capability in hydrogen production and knowledge of the chemical processes involved. Knowledge-sharing and skills development, such as through hosting research students, could justify additional funding.

This is broadly similar to the approach the federal government took to develop experience with large-scale solar power generation through the Solar Flagships policy, and the subsequent Large-scale Solar Program. Under these programs, significant government funding brought forward investment in mature but high-cost technologies, to bring down those costs and improve local knowledge. Both programs required proponents to produce or fund knowledge-sharing reports to support this objective.[a]

a. Department of Resources, Energy and Tourism (2011); and ARENA (2017).

existing integrated steelworks. The cost could be $20 to $30 per tonne of carbon dioxide avoided – higher than the cost of abatement purchased through the Emissions Reduction Fund,[101] but lower than typical recent prices for emissions permits in the EU emissions trading scheme.[102] It is an affordable step towards decarbonising Australia's heavy industry.

The federal government should consider a procurement mandate for sustainable aviation fuels. Biofuel plants can be built at a smaller scale, allowing a range of producers to create a competitive market for these fuels. A procurement mandate could reduce emissions and create significant regional economic opportunities – it could bring hundreds of jobs to places such as Collie, Portland, the Latrobe Valley, and central Queensland (Figure 3.4 on page 33).

The cost of a biofuel purchase scheme would depend primarily on Australian production costs and the mandated share of biofuel use. Internationally, biofuels are about 2-to-3 times the price of fossil-based jet fuel,[103] and this means that replacing 10 per cent of jet fuel with biofuel would increase domestic ticket prices by about 2-to-4 per cent.[104] Further investigation is warranted to better understand the costs involved for air travellers, how those costs might reduce over time, and the rate at which technologies proven overseas could be deployed in Australia. Costs should be further managed by gradually increasing the share of biofuel required over time – enabling manufacturers to identify the lowest-cost supply options and adopt the latest technology.

101. Clean Energy Regulator (2020).
102. Intercontinental Exchange (2020).
103. ETC (2018c, p. 13). The ETC considers that this will decline over time. Biofuel costs will vary depending on feedstock availability and cost, and the conversion technology used. The biofuel cost premium will also be higher at times of low crude oil prices, as have emerged in 2020.
104. Grattan analysis of Qantas (2019) indicates that fuel makes up about 20 per cent of the cost of a domestic airline ticket (higher for international). It follows that doubling the price of fuel would increase ticket prices by about 20 per cent for a 100 per cent biofuel mandate, or about 2 per cent for each 10 per cent mandated.

This policy is similar to one being considered in Europe.[105] Australia will be well placed to learn from that process – in terms of both policy design and cost impacts. Care will be needed to ensure that the policy doesn't interact with differing fuel tax treatments in a way that creates perverse or unexpected outcomes. And Australia will need to ensure that fuels supported under this policy comply with existing internationally-approved technical standards for alternative aviation fuels.[106]

Green ammonia offers a substantial market opportunity for Australia (Section 3.8 on page 34). But the case for specific policy action on green ammonia is not as strong as for green steel or biofuels. Australia has an established ammonia industry and there are no major technical barriers to blending renewable hydrogen into existing plants. Provided Australia continues efforts to bring down the local cost of renewable hydrogen – such as through trials to build capability and efforts to reduce the cost of storage (Section 4.3) – it will be well-placed to produce green ammonia as demand for this product matures and the costs of hydrogen reduce.

4.3 Efforts to bring down hydrogen costs must continue

Australia and other countries have recognised renewable hydrogen's potential as a low-emissions fuel and industrial feedstock. The cost of electrolysers will come down as their use increases, through economies of scale in production and through technological improvements.

105. European Commission (2020).
106. ASTM International approves jet fuel standards for commercial use, including specific types of sustainable aviation fuel: ASTM International (2018). It recently approved a sixth production process for making commercial sustainable aviation fuel: CAAFI (2020).

Australian governments, through the COAG Energy Council's National Hydrogen Strategy, have signalled support for pilot projects using renewable hydrogen. These will build local skills and familiarity with installing and using this technology, as well as with commercial aspects of their operation. The federal government is providing funding in this area.[107] And the federal Energy Minister, Angus Taylor, has stated his commitment to drive hydrogen costs below $2 per kilogram.[108]

Low-cost hydrogen storage is important to producing cost-competitive and continuous hydrogen supply using variable renewable energy from solar and wind. Salt cavern storage is likely to be the lowest-cost form of storage, and Australia is behind countries such as the US and Germany in building this kind of storage.

Australia does have prospective underground salt formations that could be suitable for storage – including in southern Queensland[109] – but not a lot is known about them. Governments could position Australia well for future hydrogen use, including for green steel, by funding and publishing pre-commercial geotechnical studies of these potentially important resources, as governments do for petroleum resources.

4.4 State governments have a crucial facilitating role

Land-use planning will be an important and complex element of accommodating new global-scale manufacturing industries. State governments have a crucial role here, because they have primary responsibility for approving the conditions of major industrial projects. Finding suitable industrial land, and allaying local community concerns, is often difficult. The regions and communities that currently host carbon-intensive industries are generally best placed to balance these pressures, but strategic long-term government planning will help.

107. ARENA (2020).
108. Taylor (2020).
109. Feitz et al (2019, p. 33).

Existing industrial and mining sites are likely to be very good locations for future clean energy industries. They have infrastructure connections, such as power, water, rail, and road, and buffer zones to manage noise, dust, and visual impacts on neighbours. State governments regulate the rehabilitation of mines and the decommissioning of industrial sites, and so have a crucial role in ensuring smooth transition of sites from one use to another.

State and federal governments can help workers retrain to capture new opportunities. Given the size of the potential retraining task, the two tiers of government should share the funding burden. State governments should lead efforts to identify the skills needed by new industries. This assistance should reassure potential investors that the skills they need will be available. State governments should also work with employers and unions to assist with workforce continuity as Australia transitions from old activities to new.

Local governments and local communities also have an important role. Many people in carbon-intensive regions recognise the challenges facing their existing industries, and are looking to diversify their local economies. For example, the Hunter region in NSW has developed an economic diversification plan involving state and local governments,[110] and the Victorian Government has established the Latrobe Valley Authority to help that region diversify beyond coal-fired electricity generation.[111] The Queensland Government has also created a Just Transitions unit to help local communities manage their transition to new industries.[112] Local community support is crucial if new industries are to grow, so close engagement with local government will be important.

110. NSW Government and Hunter Joint Organisation of Councils (2018).
111. Latrobe Valley Authority (2020).
112. Queensland Government (2020).

Appendix A: Technical notes, assumptions, and benchmarking

A.1 Green manufacturing: technical appendix

A.1.1 Pathways to steel

Iron ore – the mineral dug out of the ground – has to be processed before it becomes the steel we see around us every day. There are two fundamental steps. The first is stripping out the oxygen atoms from the iron ore to produce iron metal – this is also called ‘smelting’. The second is altering the chemical composition of the metal to give it the properties of steel; this includes adding or removing a small amount of carbon.

There are two main methods of producing iron from iron ore. The first involves a blast furnace: in this process pieces of iron ore[113] are stripped of oxygen (a process called ‘reduction’) and then melted in the furnace. Heated air is blown into the base of the furnace, and coke (lumps of mostly carbon made from metallurgical coal in coke ovens) is burnt there to produce heat and make the gases necessary for reduction to occur. The gas exiting the furnace top is a mixture of carbon dioxide and carbon monoxide, with a small amount of hydrogen. This is used as a fuel in subsequent steel reheating and shaping in the steelworks. Blast furnaces are used as part of the integrated steel-making process (see Figure A.1 on the following page). This means that the iron metal from the blast furnace is then transported to another furnace – the basic oxygen furnace – to make steel. Here, oxygen is blown onto the molten iron (plus some steel scrap) to refine the iron and produce low-carbon steel. Again, carbon dioxide is produced in the process. This combined method is the most common way steel is produced today.

113. The pieces of iron ore are typically a blend of lump ore (larger pieces from the mine), pellets (hard spheres of agglomerated iron ore dust, known as fines), and sinter (irregular lumps of agglomerated iron ore fines).

The second method is called ‘direct reduction’ (see Figure A.2 on page 41). Iron ore is heated but not melted in a shaft furnace with ‘reductant gases’, typically a blend of carbon monoxide and hydrogen. These are usually made by reacting natural gas and steam in a steam methane reformer, but can also be made by gasifying coal. The reductant gases play the role that coke plays in a blast furnace, stripping oxygen from the ore. Carbon monoxide becomes carbon dioxide, and hydrogen becomes water.

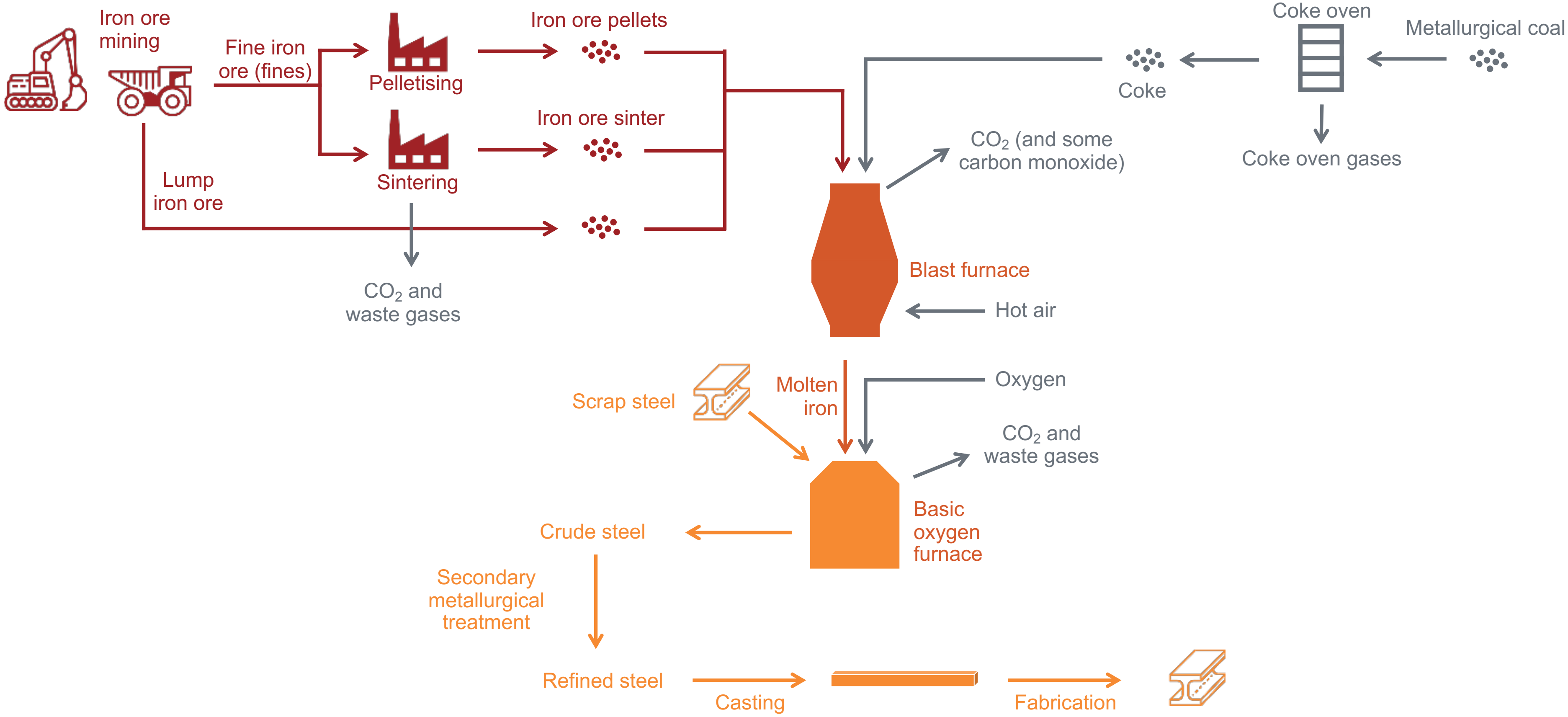
The iron from this process – ‘direct reduced iron’ – contains a lot of impurities, and so needs to be melted down in an electric arc furnace. Scrap steel can also be recycled in an electric arc furnace, and is often blended in with the direct reduced iron.

Both methods produce carbon dioxide at various points in the process. To make low-emissions steel, either the carbon dioxide needs to be captured and permanently stored, or the process needs to use renewable inputs. Renewable coke and natural gas from biomass are not economic; renewable hydrogen is more prospective. That leaves four major ways of producing low-emissions steel:

1. Using carbon-capture and storage (CCS) in an integrated steel-making process;
2. Using CCS in a gas-based direct reduction process;
3. Using renewable hydrogen in a direct reduction process;[114] or
4. Using hydrogen derived from fossil fuels in a direct reduction process, capturing the carbon dioxide emitted in the hydrogen production step.

114. A small amount of natural gas is also needed to help maintain the temperature in the shaft. This could be replaced with biogas to further reduce emissions.

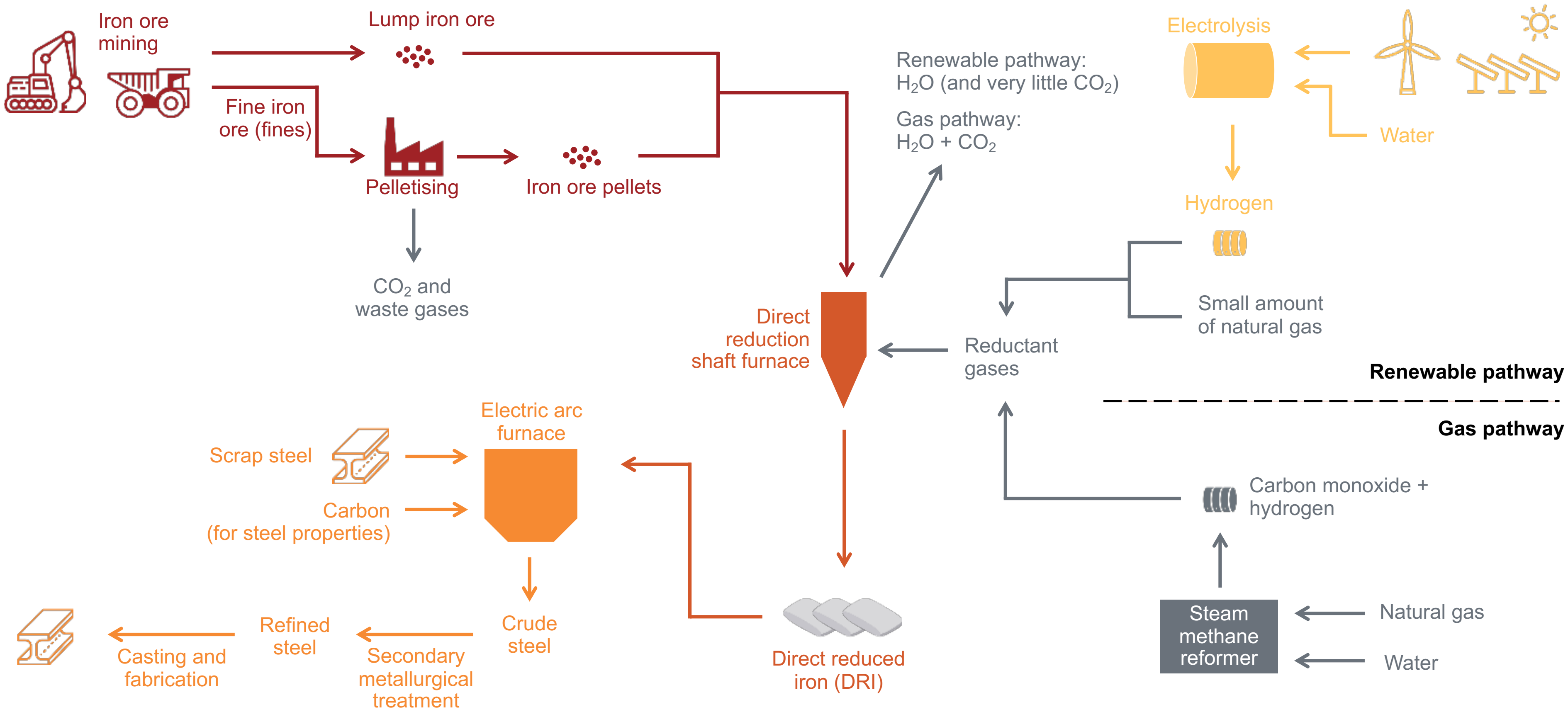
Figure A.1: Integrated steel-making



Note: Scrap steel is added to the basic oxygen furnace to control the temperature.

Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

Figure A.2: Direct reduction pathways using either renewable hydrogen or natural gas



Notes: Low-emissions pathways also require that low-emissions electricity be used in each step. Gasified coal can be used in place of natural gas.

Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

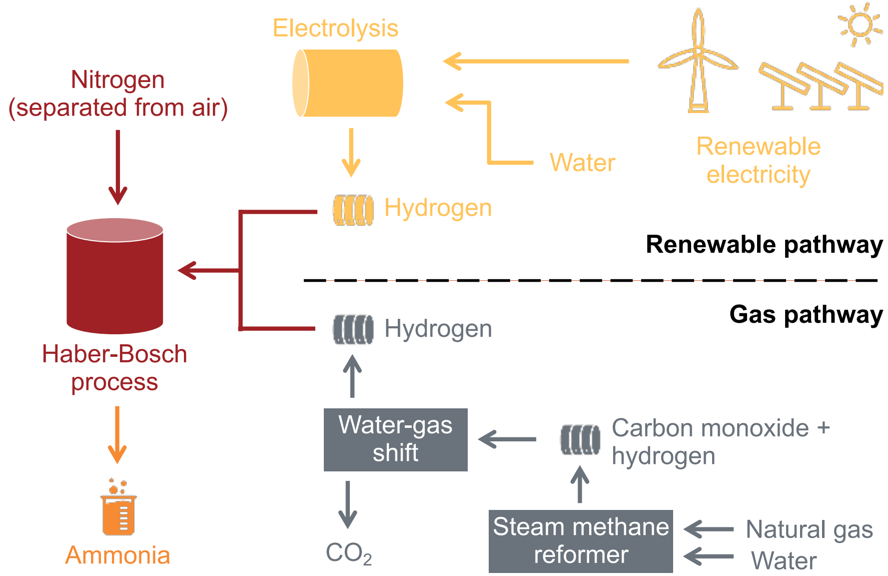
A.1.2 Pathways to ammonia

Ammonia is made of nitrogen and hydrogen. The elements are combined in the Haber-Bosch process to produce liquid ammonia.

Nitrogen is abundant – more than three-quarters of air is nitrogen, and so it simply needs to be separated from the other gases in the air. Hydrogen, on the other hand, needs to be chemically produced. Currently, the most common way of producing hydrogen is combining steam and natural gas (methane) in a steam methane reformer (Figure A.3). This produces a blend of hydrogen and carbon monoxide. Using the water-gas shift reaction, more steam can be converted to hydrogen, and the carbon monoxide is converted to carbon dioxide.

To make low-emissions ammonia, the hydrogen needs to be produced in a low-emissions way. The two main options are 'green' or 'blue' hydrogen. The green route involves splitting water into hydrogen and oxygen using an electrolyser, powered by low-emissions electricity (in Australia, this is more likely to be renewable electricity than nuclear or fossil-fuel generation with CCS). The blue route is the same as today's method – a fossil fuel such as natural gas is converted into hydrogen and carbon dioxide – but the carbon dioxide is captured and stored permanently.[115]

Figure A.3: Renewable and non-renewable pathways to ammonia synthesis



Source: Grattan analysis. Some icons sourced from flaticon.com (2020).

115. Using a biomass source instead of a fossil fuel would be carbon-neutral, but is unlikely to be as economic.

A.2 Estimating green commodity production costs

Table A.1: Core economic assumptions

Parameter	Assumption	Notes
Return on capital	10% per annum	Pre-tax return
Economic life	25 years	Not equivalent to physical plant life
Plant load factor	90%	To adjust rated capacity to output
Long run FX	0.7 A$/US$	Slightly lower than five-year average of 0.74; historic conversions done using historic rates: Investing.com (2020); forward-looking conversions done using long-run rate

Table A.2: Steel cost assumptions – steel plant

Cost element	Unit	Assumption		Sources and notes
DRI				
Iron (pellet) input	tonne iron ore per tonne DRI	1.4		Energiron (2020b)
Natural gas input	GJ natural gas per tonne DRI (gas-based)	9.9		Energiron (ibid)
	GJ natural gas per tonne DRI (hydrogen-based)	1.9		Midrex (2017)
Hydrogen input	kg hydrogen per tonne DRI (hydrogen-based)	72		Midrex (ibid)
Water input	kL per tonne DRI (gas based)	1.3		Energiron (2020b)
	kL per tonne DRI (hydrogen based)	2.2		Includes electrolysis water of 15 L per kg H_2
Capital cost	US$/Mt rated DRI capacity (gas based)	428		Benchmarked based on Nucor (2013), voestalpine (2017a) and Cleveland Cliffs (2017)
	US$/Mt rated DRI capacity (hydrogen based)	396		10% reduction assumed for Midrex plant as gas reformer not required
Labour input	FTE/Mt rated DRI capacity (gas based)	78		Benchmarked based on Nucor (2013), voestalpine (2017b) and Cleveland Cliffs (2017)
	FTE/Mt rated DRI capacity (hydrogen based)	73		10% reduction assumed for Midrex plant as gas reformer not required
DRI input to steel-making	tonne DRI per tonne steel	1.17		Energiron (2013)
Electric arc furnace				
Electricity input	MWh per tonne of steel (hot DRI feed)	0.43		Energiron (ibid), with Grattan adjustment to reflect carbon content of DRI
Electricity input	MWh per tonne of steel (cold DRI feed)	0.52		Energiron (ibid)
Water input	kL per tonne of steel	1.6		Colla et al (2017)
Capital cost	US$/Mt rated steel capacity	144		Benchmarked based on Steel on the Net (2018), US Steel (2019) and Coyne (2015)
Labour input	FTE/Mt rated steel capacity	167		Grattan calculation based on Steel on the Net (2020a)
Crude steel input to cast steel	tonne crude steel to cast steel	1.02		IEA Environmental Projects (2013, Figure E-2)
Casting and hot rolling		**Casting**	**Hot rolling**	
Electricity input	MWh per tonne of steel	0.01	0.11	IEA Environmental Projects (ibid, Table C-3)
Water input	kL per tonne of steel	1.0	2.2	IEA Environmental Projects (ibid, Table D-12)
Capital cost	US$/Mt rated steel capacity	54	123	IEA Environmental Projects (ibid, Table E-4)
Labour input	FTE/Mt rated steel capacity	100	120	Grattan calculations based on IEA Environmental Projects (ibid, Table D-6)

Table A.3: Steel cost assumptions – input costs

Parameter	Units	Eastern Australia	Pilbara	Pilbara (low cost)	Bunbury	Japan	Indonesia	Sources
Iron ore pellets	A$/t input	152	152	152	152	152	152	Pellet price calculated based on a fines price, adjusted to pellet iron concentration, plus a pellet premium. Fines price from Steel on the Net (2020b); pellet premium of US$37 per tonne from Ferrexpo (2017).
Natural gas	A$/GJ	8	4	4	5	8	4	Eastern Australian gas prices based on lifecycle costs published in ACCC (2018, p. 22), with an allowance for transport and mark-up. Pilbara gas prices based on AEMO (2019, p. 62). Bunbury gas prices are Pilbara gas prices plus transport costs from DBP (2020). For simplicity, Indonesia assumed to have Pilbara gas prices; Japan assumed to have Eastern Australian gas prices.
Purchased electricity	A$/MWh	107	143	143	143	179	179	Wholesale costs plus a US$25/MWh retail and transmission cost component. Eastern Australian prices based on Blakers et al (2017a). Japan assumed to have the same electricity price as Indonesia; both based on Wang et al (2018). Pilbara electricity prices based on a study of south-west WA: Blakers et al (2017b)
Labour	A$/hour	57	97	77	57	44	7	Australian and Japanese wages are based on national wages from OECD (2018), increased by 30% to reflect the level of wages in Australia's steel industry based on Grattan analysis of ABS (2017). Indonesian wages based on Krakatau Steel (2018), Krakatau Steel (2019) and PT Gunung Raja Paksi Tbk (2019)
Capital cost (locational factors)	% of benchmark cost	130%	182%	156%	130%	100%	100%	Locational cost factors based on LNG plants built between 2014 and 2018, cited in Songhurst (2018).
Maintenance cost (locational factors)	% of benchmark cost	131%	203%	167%	131%	100%	59%	Calculated based on weightings of 50% for labour rates and 50% for capital cost (relative to benchmark)
Water	A$/kL	3	3	3	3	3	3	Grattan analysis based on Australian urban desalination plants listed in Australian Water Association (2020)

Note: 'Pilbara (low cost)' is the Pilbara low-cost scenario, in which capital and labour cost premia relative to eastern Australia are halved.

Table A.4: Ammonia assumptions

Sub-component	Unit	Assumption	Source	Notes
Hydrogen input	kg H_2 per tonne ammonia	176	Pfromm (2017)	
Electricity	MWh per tonne ammonia	0.3	Grattan calculations based on Pfromm (ibid)	Excludes electrolysis; air separation and ammonia condensation only
Capital cost	US$ per tonne ammonia rated capacity (gas-based)	1,124	Grattan calculations based on Incitec Pivot (2016)	Inflation adjusted to 2019 US dollars
Capital cost	US$ per tonne ammonia rated capacity (hydrogen-based)	1,011		10 per cent reduction relative to gas-based ammonia, as steam methane reformer not required.
Maintenance cost	Share of capital cost	2%	Grattan assumption	Annual maintenance cost assumed to be 2% of total (upfront) capital cost
Labour input	FTE per Mt ammonia capacity (gas-based)	81	Chemicals Technology (2020)	
Labour input	FTE per Mt ammonia capacity (hydrogen-based)	73		10 per cent reduction relative to gas-based ammonia, as steam methane reformer not required.

Table A.5: Transport assumptions

Parameter	Assumption	Units	Sources and notes
Turnaround time	6	days	Grattan assumption
Handling cost	3	A$/tonne	Steel on the Net (2020c)
Charter rate	23,774	A$/day	Grattan analysis of charter rates in Fearnleys (2020)
Charter load	175,000	tonnes	Grattan assumption for a 180,000 tonne capacity ship (Capesize)
Fuel cost	511	A$/tonne	Grattan analysis of Singapore fuel oil prices (IFO380) in Fearnleys (ibid)
Bunker fuel energy density	40	GJ/tonne	Department of the Environment and Energy (2019, Table 3) and Fritt-Rasmussen et al (2018, p. 14)
Ammonia energy density	22.5	GJ/tonne	Valera-Medina et al (2018)
Ammonia price	802	A$/tonne	Calculation based on assumptions in Table A.4, with US$2/kg hydrogen
Clean shipping fuel effective price	1416	A$/equivalent tonne	Calculation based on the above assumptions
Fuel consumption	0.16	tonnes/nautical mile	Grattan estimate based on ship charter costs, fuel costs and cargo charter quotes in Fearnleys (2020)

Table A.6: Transport costs for various routes

Route	Start port	End port	Distance (one way) Nautical miles	Time at sea (round trip) Days	Handling cost A$/tonne	Charter cost A$/tonne	Fuel cost A$/tonne	Total cost A$/tonne
Pilbara to eastern Australia	Dampier	Newcastle	3034	31	3	4	8	15
Pilbara to Japan	Dampier	Kitakyushu	3624	36	3	5	9	17
Pilbara to Indonesia	Dampier	Jakarta	1203	16	3	2	3	8
Eastern Australia to Japan	Newcastle	Kitakyushu	4403	43	3	6	11	20
Eastern Australia to Indonesia (backhaul via Pilbara)	Dampier	Jakarta	1203	16	7	2	3	12

Notes: Shipping costs assume the use of green ammonia as a low-emissions fuel. Backhaul from eastern Australia to Indonesia involves free transport from eastern Australia to Dampier using empty ships returning to pick up a new iron ore cargo; additional handling costs are incurred to move the product between ships at Dampier for further shipping to Jakarta.

Sources: Shipping distances based on sea-distances.org (2020). Calculations based on sea distances and assumptions detailed in Table A.5 on the preceding page.

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Table A.7: Renewable electricity ongoing job assumptions

Project	Proponent	Project status	Capacity (MW)	Ongoing jobs (FTE)	Jobs per MW	Source
Solar						
Walcha (Salisbury)	Walcha Energy	Proposed	600	10 to 15	0.02	Walcha Energy (2019, pp. 5, 16)
New England	UPC Renewables	Proposed	720	Up to 15	0.02	UPC Renewables (2019, p. 1)
Yarrabee	Reach Solar Energy	Proposed	900	10 to 15	0.01	Reach Solar Energy (2019, pp. viii, xi)
Average of three projects					0.02	
Wind						
Dundonnell	Tilt Renewables	Under construction	336	10	0.03	Tilt Renewables (2020)
Stockyard Hill	Goldwind	Under construction	530	Approximately 30	0.06	Goldwind (2020)
Coopers Gap	Powering Australian Renewables Fund	Under construction	453	15 to 20	0.04	AGL (2020)
Forest Wind	Forest Wind	Proposed	1200	Up to 50	0.04	Forest Wind (2019, pp. 4, 73)
Average of three projects					0.04	

A.3 Benchmark biofuel facilities

Plant	Owner	Country	Status	Start year	Primary feedstock	Main products	Process	Output (kt)	Input (kt)	Ongoing jobs	FTE/Mt output
Indian River	Ineos	US	Closed	2013	Woodwaste	Ethanol	Syngas fermentation	24	121	65	2,708
Crescentino	Versalis	Italy	Returning to service	2013	Wheat straw	Ethanol	Enzymatic hydrolysis	40	200	100	2,500
Empyro	BTG-BTL	N'lands	Operating	2013	Woodwaste	Biocrude	Pyrolysis	25			
Hugoton	Seaboard	US	Mothballed	2014	Corn stover	Ethanol	Enzymatic hydrolysis	74	330	76	1,030
Project Liberty	POET-DSM	US	Closed	2014	Corn stover	Ethanol	Enzymatic hydrolysis	59	314	70	1,185
Lappeenranta	UPM	Finland	Operating	2015	Tall oil	Biodiesel, naphtha	Hydrogenation	130		84	646
SugarFlex	GranBio	Brazil	Operating	2015	Bagasse	Ethanol	Steam explosion	65			
Iowa	Verbio	US	Closed for process conversion	2015	Corn stover	Ethanol	Enzymatic hydrolysis	89		90	1,016
Edmonton	Enerkem	Canada	Operating	2016	MSW	Ethanol, methanol	Syngas synthesis	30	100		
Cote Nord	Ensyn	Canada	Operating	2018	Sawdust	Biocrude	Thermochemical	36	65	30	833
Lakeview	Red Rock	US	Construction	2020	Woodwaste	Biocrude	Syngas synthesis	51	150	105	2,055
Sierra	Fulcrum	US	Construction	2020	MSW	Biocrude	Syngas synthesis	36	193	120	3,355
Kastet	Pyrocell	Sweden	Construction	2021	Sawdust	Biocrude	Pyrolysis	25	80		
Lieksa	Green Fuel Nordic Oy	Finland	Construction	2021	Sawdust	Biocrude	Pyrolysis	18		20	1,111

Notes: N'lands is the Netherlands. MSW is municipal solid waste. Tall oil is a wood pulp residue. Blank cells indicate data not available.

Sources: Company websites and miscellaneous sources.

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